Palaeoenvironments and Biostratigraphy of Early Miocene Waikari Formation and Mt Brown beds, North Canterbury, New Zealand.

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ABSTRACT

The Waikari Formation and Mount Brown Formation of North Canterbury represent inner to outer shelf deposits of siltstones, sandstones and limestones. The aim of this thesis was to integrate field observations, qualitative macrofossil and trace fossil data, and quantitative foraminiferal data to determine biostratigraphy, palaeoenvironments and reconstruct the palaeogeography of the Waipara/Waikari area through the Early Miocene. Multivariate data analysis of foraminifera data using Bray-Curtis two way and detrended correspondence analysis was key to determining original depositional environments.

The Waikari Formation consists of blue grey siltstones and brown fine sandstones of Otaian age. In the study area three members were identified; Pahau Siltstone, Scargill Siltstone and Gowan Hill Sandstone. A key feature of the Pahau Siltstone is the high glauconite content and heavy bioturbation caused by the trace *Zoophycos.* The Scargill Siltstone is recognised by the lower glauconite content compared to the Pahau Siltstone and a change in dominant trace to *Ophiomorpha*. The Gowan Hill Sandstone contains light grey siltstones and brown fine sandstones. The faunal component of the Gowan Hill Sandstone includes brachiopods, bryozoa and bivalves; and is distinguished by higher faunal component compared to the two other members of the Waikari Formation. Multivariate analysis indicated that the Waikari Formation was deposited in mid to outer shelf water depths.

The Mount Brown Formation is dominated by yellow sandstone and also contains the Whiterock Limestone, the discontinuous Onepunga Shell Beds, North Dean Limestone and Red Crag Limestone members that are late Otaian to Altonian in age. The Whiterock Limestone is a bryozoan rich limestone of Otaian age. *Celleporaria papillosa* are abundant along with branching bryozoans, and the abundance of bryozoa in the limestone is typical of a cool-temperate environment. The Onepunga Shell Beds are lenses of molluscan dominated cast limestone that was deposited in a mid-shelf environment that is Altonian in age. The North Dean Limestone is characterised by cross bedding and is Altonian in age. The limestone represents a higher energy depositional environment in inner shelf water depths with non crossbedded units from the midshelf. Foraminifera identified in the North Dean Limestone include *Elphidium crispum crispum* and *Amphistegina* sp, typical of inner to mid shelf environments in a warm subtropical, temperate depositional environment.

The Red Crag Limestone members are Altonian in age and are characterised by brachiopod and molluscan fauna. Red Crag Limestone 1 has limited fauna occurs discontinuously. Red Crag Limestone 2 is characterised by brachiopod and molluscan fauna. The brachiopods are more dominant in this unit. Red Crag Limestone 3 reflects subtle changes from Red Crag Limestone 2 with molluscan fauna being more prominent.

Overall, the Waipara-Waikari region, North Canterbury experienced a shallowing from outer shelf to mid shelf environment during the Otaian stage reflected in the Waikari Formation deposits, and mid to inner shelf depositional environment during the Altonian stage, reflected in the Mount Brown Formation deposits.

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Chapter 1

Introduction

The North Canterbury region presents an ideal location to study the Tertiary rocks as there are abundant and well documented continuous outcrops. The basins and ranges in the North Canterbury region are associated with the evolution of the Australian-Pacific plate boundary (Forsyth et al. 2008). Prominent ridges are seen trending to the north east exposing Tertiary limestones and sandstone that form the basis of this study.

This study examines Early Miocene rocks of the Waikari Formation and what have been called the Mount Brown Beds, but will be described as Mount Brown Formation later in this thesis. These two successions consist of less well indurated beds of the Waikari Formation; and well indurated Mount Brown Beds that creates a 'dip and scarp' topography seen throughout the study area. The Mount Brown Beds are better lithified and define the topographic highs of Mt Brown, the 'Deans Range' and beyond Weka Pass to Mt Donald.

1.1 Study Area and Regional Geology

1.1.1 Location

The area involved in this thesis is in the Waipara-Waikari region, north west of Amberley, North Canterbury, New Zealand. The main study area extends from the north eastern side of Mt Grey, extending east through Onepunga Farm, to Mt Brown and along the Deans Range (Fig. 1). The study area is extended further to the west up through Karetu Downs, McDonald Downs up to into Pyramid Valley, Waikari (Fig.1).

1.1.2 Lithostratigraphy

Basement rocks in the Canterbury region consist mainly of Torlesse Supergroup, late Palaeozoic and Mesozoic indurated non-marine and marine sedimentary rocks (Field et al. 1989; Rattenbury et al. 2006; Forsyth et al. 2008)

Overlying this basement rock; are softer sedimentary cover rocks deposited during and after rifting from Gondwana (Forsyth et al. 2008). In North Canterbury these are fluvial deposits, marine sandstone mudstone, greensand, calcareous mudstone and limestones, of the Eyre Group. From Mt Grey up to the Motunau area there are six formations in the Eyre Group; the Broken River Formation, Loburn Mudstone, Waipara Greensand, Ashley Mudstone, Karetu Sandstone and Amuri Limestone (Forsyth et al 2008). The deposits ranged from shoreface to outer shelf (Field, Browne et al. 1989; King et al. 1999). The age range of the Eyre Group ranges from Late Cretaceous to Early Oligocene (Forsyth et al. 2008). The Amuri Limestone ranges from age from Early to Late Eocene at Haumuri Bluff; at Hurunui River it is Late Eocene; and at Waipara River the limestone is Oligocene (Field, Browne & others 1989).

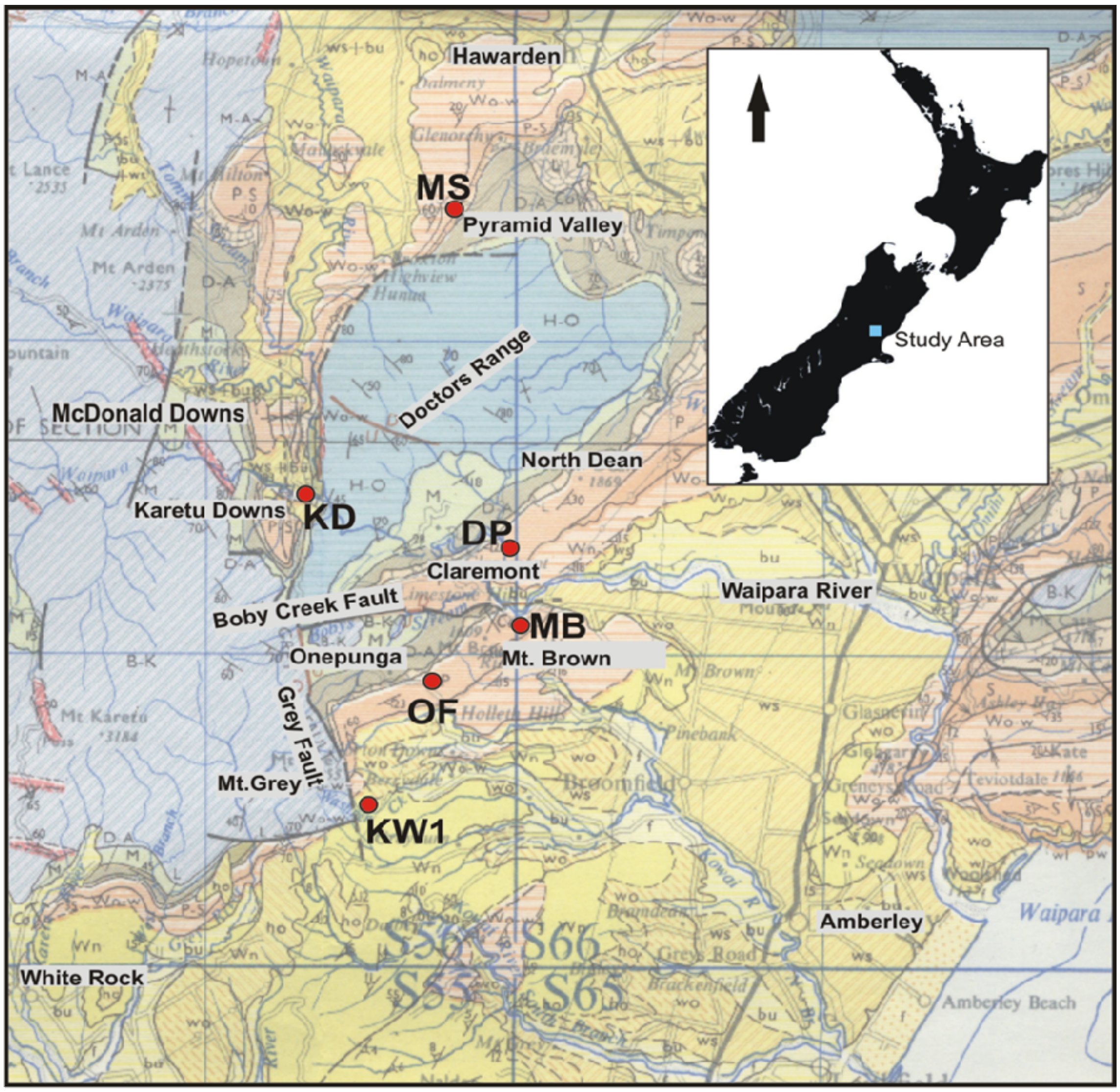


Figure 1. Locality map of the Waipara-Waikari area. Study area indicated in blue at top left. Map modified from Sheet 18 (Gregg et al. 1964).

The Motunau Group sedimentary rocks are widespread in northern Canterbury (Field and Browne 1987), and include the rocks that are the focus of this thesis. The group ranges in age from Late Oligocene to Late Pliocene (Browne and Field 1985) and is dominated by fine detrital sedimentary rocks and limestones (Field and Browne 1987). The group represents a period of mainly shallow marine sedimentation which culminated in a marine regression (Forsyth et al. 2008).

The Motunau Group consists of a number of formations that vary laterally from Esk River up to Motunau. The formations seen in the study include; the Omihi Formation (Weka Pass Limestone), Waikari Formation, Mount Brown Formation and the Kowai Formation. The Waikari Formation and the Mount Brown Beds are identified within the Motunau Group in the North Canterbury region. The Mount Brown Beds are overlain by the Kowai Formation; the formation consists of weathered, greywacke-clast conglomerate with interbedded sandstone, siltstone, mudstone and carbonaceous layers (Forsyth et al. 2008).

1.1.3 Structure and Geomorphology

The landscape in the North Canterbury area reflects influences of tectonics and sediment deposition (Forsyth et al. 2008). East of the Southern Alps the ranges and basins have been formed by tectonic movements that were associated with the Australian-Pacific plate boundary (Forsyth et al. 2008).

Ranges in the region are the result of uplift which led to faulting and folding in the region and the basin fill alluvial fans and plains (Forsyth et al. 2008). In the Waipara River region river terraces show tilting that is associated with folding across the hills.

The limestones along the ridgelines in the Waipara to Waikari region form a distinct landscape. The Mount Brown units are exposed 20 km along escarpments extending from the Grey Fault located at the base of Mt Grey across Onepunga, Mt Brown, and the Deans Range (Fig. 2) extending up into Weka Pass. The Waikari Formation deposits are found in topographic depressions and the best exposures of this occur in the Waipara River locations where there is exposure of Waikari Formation, and Mount Brown beds occur to the west at Karetu Downs, McDonald Downs and Pyramid Valley.

The ranges are from the result of uplift by faulting and/or folding (Forsyth et al. 2008). The basins lie in areas of lesser uplift or subsidence (Forsyth et al. 2008). Formations of alluvial fans and plains have formed with the basins, in many places these landforms have been incised periodically to form terraced valleys and filled with Quaternary deposits. The North Canterbury fold and fault belt consists of a series of en-echelon NE-trending anticlines and synclines typically bounded to the west by high-angle faults (Field and Browne 1989).

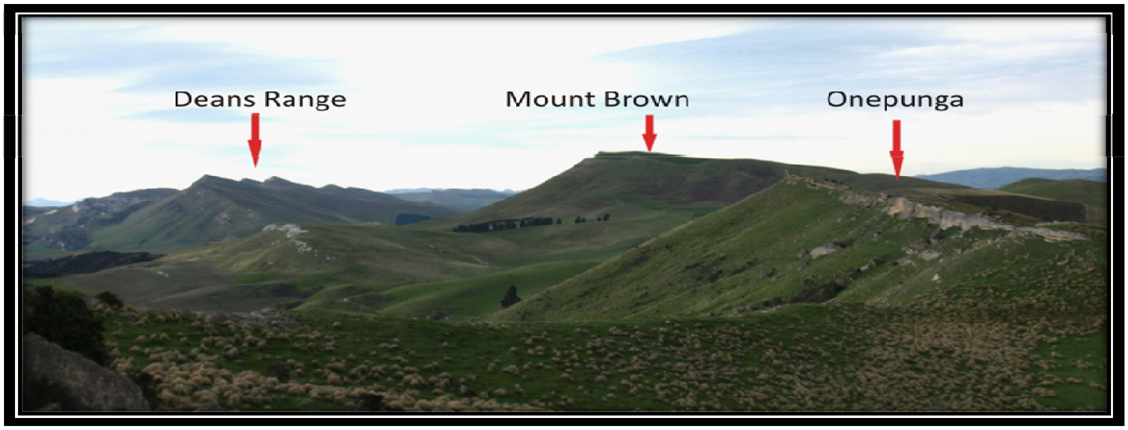


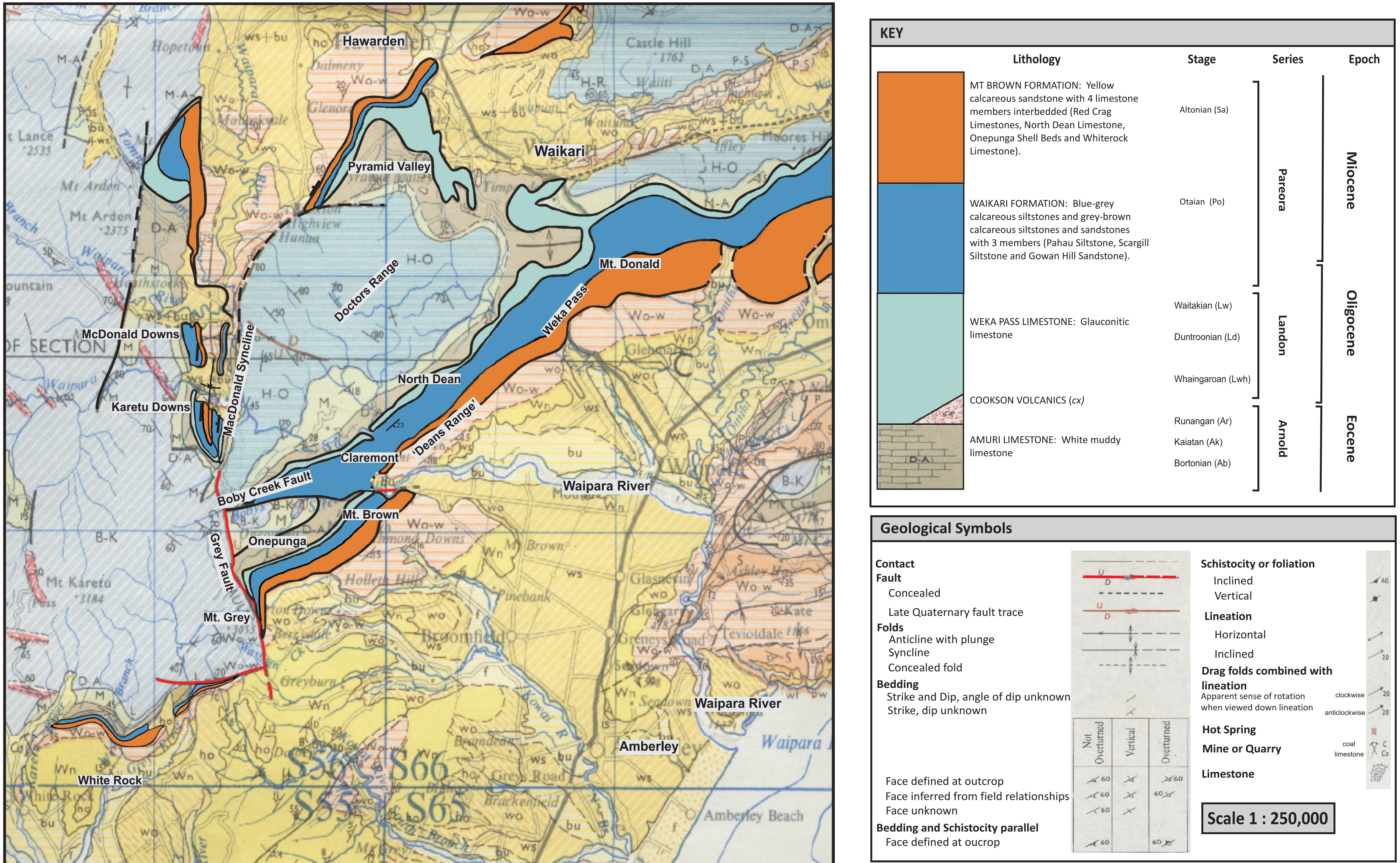
Figure 2. Image looking to the north east of the Mount Brown Beds exposed along the escarpment of Onepunga, Mt Brown and Deans Range.

Structural features in the study area are Upper Cretaceous and Tertiary aged rocks that have been uplifted and folded into north east trending folds and synclinal folds (Gregg et al. 1964; Forsyth et al. 2008). In the study area structural features seen include; the McDonald Syncline, Doctors Anticline and Onepunga Anticline (Fig. 3). Faults in the region include; the Grey Fault, Boby Creek Fault and the Karetu Fault (Fig. 3).

The ranges and basins east of the Southern Alps have been formed by tectonic movements associated with evolution of the Australian-Pacific plate boundary (Forsyth et al. 2008). The early Miocene deformation was associated with the onset Australian-Pacific plate boundary from a passive to active margin (Forsyth et al. 2008). Wilson (1963) and Andrews (1968) suggest the Mt Grey area was probably rising during this time along bounding faults.

The McDonald Syncline occurs in the north west corner of the study area the MacDonald Syncline plunges north under McDonald Downs (Fig. 3). The Waikari Formation and Mount Brown Beds are seen steeply dipping in the south branch and middle branch of the Waipara River. Much of the area is covered by the Kowai Formation and Quaternary deposits (Fig. 3).

North of the south branch of Waipara River the basement rocks are separated from steeply dipping Tertiary deposits by a reverse fault (Wilson 1963). The Karetu Fault on the eastern side of the MacDonald syncline; it is a thrust fault on the western side of Doctors Range, which consists of basement rock. The fault extends south-south west for around 3km (Wilson 1963).



Modified from Sheet 18 (Gregg et al. 1964)

Figure 2. Distribution of the Waikari Formation and Mount Brown Formation in the Waipara-Waikari Area

Onepunga Anticline is an east striking fold that is separated from the Doctors anticline in the north by Boby's Creek Fault and the Grey Block (Mt. Grey) to the west by the Grey Fault (Wilson 1963). The northern limb of the anticline has been removed by faulting. The southern limb forms prominent escarpments extending to the north east where the Mount Brown Beds are seen along the skyline (Fig. 3). The anticline nears the Grey Fault to the south, the strike of the southern limb swings from west to south (Wilson 1963). The Grey Fault (Fig. 3) is a north-striking reverse fault (Wilson 1963) seen at the south eastern limit of the study area.

The Boby Creek Fault strikes to the east, the upthrown side is on the south side of the fault. Displacement can be clearly seen on the Deans Range where the Mount Brown succession has have been displaced about 1.6km from their correlatives on Mount Brown (Fig. 3). The fault outcrops in the Waipara River dragging Mount Brown units upward. The fault can be traced from the Grey Fault to Waipara River (Fig. 3).

Much of the late Cretaceous to Pliocene cover sequence was eroded from many uplifted areas but was preserved in intraland basins, beneath the Canterbury Plains, northern Canterbury and offshore (Forsyth et al. 2008).

1.1.4 Geological Development of North Canterbury

The Waikari Formation represents siltstones and sandstones which were deposited during the Otaian stage and the Mount Brown Beds represent a sequence of sandy limestones that were deposited during the Altonian stage. The oldest limestone of the Mount Brown Beds is inferred to interfinger members of the Waikari Formation (Andrews, 1963; McCulloch 1981).

In the Late Oligocene; a slow, persistent rise in relative sea level occurred from the mid-Cretaceous to mid-Tertiary, this is characterised by transgressive sedimentation patterns, culminating in maximum marine inundation of proto-New Zealand (King et al. 1999). The palaeogeography of the late Oligocene in the region is interpreted as having reduced land areas and extensive shallow marine platforms formation (King et al. 1999).

From the early Miocene there has been a long-term lowering of sea level and regressive depositional patterns have predominated (King et al. 1999). The North Canterbury region represents a period of increased deformation which resulted in uplift, folding and faulting. The area also represents the development of a regressive sedimentary sequence that is seen throughout the Canterbury region (Forsyth et al. 2008).

The Early Miocene tectonic deformation in the North Canterbury area is associated with the Australian-Pacific plate boundary (Forsyth et al. 2008). Deformation began in the late Cenozoic from regional oblique plate-plate compression which is reflected by facies changes in the North Canterbury area (Bradshaw 1975). The onset of convergent tectonics led to the expansion of land areas and an increase in terrigenous sedimentation in basins in the Canterbury Region (King et al. 1999).

In the North Canterbury area there is evidence of deformation in the Otaian stage, it is the first indication of increased deformation occurs in the early Miocene which is inferred to have led to debris flows during the deposition of the Mount Brown Beds (McCulloch 1981; Browne and Field 1989). The Waikari Formation and Mount Brown Beds reflect some of these facies changes that occurred at the onset of the compression.

Palaeogeographic reconstructions in the Early to Middle Miocene suggest there were warm subtropical waters extending further south into the ocean around New Zealand (Cooke and Nelson 2001). This marks a change from the cold/cool waters that were flowing over the New Zealand plateau and deposited cool water carbonate facies during the Oligocene (Cooke and Nelson 2001).

Previous authors that have described the Waikari Formation and the Mount Brown Beds; described the lithologies and inferred a shallowing up in the sequence, from a relatively deep outer shelf area; the Waikari Formation, to a relatively inner to mid shelf moderate to high energy environment; the Mount Brown Beds.

Macrofossil and microfossil faunal composition in the Waikari Formation and Mount Brown Beds will reflect changes in the depositional setting in the Early Miocene.

Which reflects the onset of Both the Waikari Formation and Mount Brown Beds contain a number of macrofossils and microfossils that will be used to reconstruct the biostratigraphy, palaeoenvironment, and determine the local palaeogeography of the early Miocene sequence in the Waipara-Waikari region.

This project aims to detail the biostratigraphy and depositional environments of the Waikari Formation and the Mount Brown Beds in the Waipara to Waikari region. Existing regional studies have given us a broad understanding of the stratigraphy and palaeoenvironment during the Early Miocene. The depositional environment, palaeoenvironment and biostratigraphy of the

Waikari Formation and Mount Brown Beds will increase our understanding during the Early Miocene in the North Canterbury region.

This will be done using multiple proxies combining foraminifera, brachiopods, bivalves, trace fossils, bryozoan and sedimentary features of the Waikari Formation and the Mount Brown Beds. In addition the foraminifera will also be used in multivariate analysis to interpret other environmental factors during deposition in the Early Miocene. Combining the macrofossils, microfossils, trace fossils and sedimentary features will further enhance our understanding of the North Canterbury region during the Early Miocene.

1.2 Previous Research

Early researchers (Hector 1869; Haast 1871) described the abundant Tertiary sequences that overlay Mesozoic deposits in the North Canterbury region and a substantial amount of published work has come out of the region. Early work by Hector (1869), Haast (1871) was primarily to determine the overall geology of the region and also identified the Waikari Formation and the Mount Brown Beds. Throughout these publications Waikari Formation was referred to as the 'grey marls' and the Mount Brown Beds were infrequently mentioned and nothing more than a brief description of the extent in relationship to other units (Nomenclature will be discussed in Chapter 2). The Waikari Formation and the Mount Brown Beds have had various descriptions over time and remain poorly defined.

Thomson (1920) revised the Mount Brown Beds and provided a thorough review of all work that had previously been done. Thomson (1920) divided the Mount Brown Beds into five limestones, which were designated oldest to youngest by letters A to E. Schofield (1949) a geological map of the McDonald Downs and Waikari District was constructed. A number of stratigraphic columns were also produced and determined relative ages by using foraminifera. There was little palaeoenvironmental interpretation based on data, as the thesis was primarily for mapping.

Andrews (1960) first investigated the lower Otaian horizon of the Waikari Formation and constructed a number of stratigraphic columns with the aim of determining the shape of the basin and provenance analysis. Andrews (1960) interpreted that the lower Waikari Formation formed in a single depositional basin and that the sands and silts were deposited on a stable shelf. The basin was described as elongate, trending NNE – SSW. Andrews (1960) interpreted sedimentary structures observed in the Waipara River were deposited in the basin by turbidity currents or periodic storm events.

Andrews (1968) investigated the pattern of sedimentation during the early Otaian, of the lower Waikari section in North Canterbury, by looking at stratigraphic relationships, sedimentary structures, textures and gross composition. Data from this study was interpreted that the Waikari Formation was deposited in a single depositional basin, which in turn was part of a broader continental shelf. The centre of the basin was determined to be north east of Waikari.

Wilson (1963) examined the geology of the Waipara subdivision and determined that the Tertiary units examined in the region consist of units that are coarsening up the stratigraphic sequence, which indicated to Wilson (1963) 'a progressive shallowing of the sea'. In this paper there had been a substantial amount of macrofossil and microfossil identification but there was a lack of information regarding the palaeoenvironmental interpretations.

In 1978, onshore drilling was undertaken by New Zealand Geological Survey to the south east of the main study area. Edwards et al (1978) investigated the overall biostratigraphy of the core, by looking at the foraminifera to determine the relative ages and palaeoenvironments. Edwards et al (1978) suggested environments of the Mount Brown succession indicated near shore, inner to mid shelf depths. The environment interpretation for the Waikari Formation was mid to outer shelf water depths.

McCulloch's (1981) thesis revised interpretations by Andrews (1968) regarding it being a single depositional basin and suggested that the oldest limestone of the Mount Brown beds were deposited in an area of the basin where it was more sheltered and associated with a submarine topographic high. Deposition of the Mount Brown succession was interpreted to have been deposited by debris flows, which were triggered by uplift and faulting in the region in the early Miocene. The oldest limestone from the Mount Brown beds is inferred to interfinger the Waikari Formation deposits (McCulloch 1981).

1.3 Thesis Aims

This study aims to redescribe the lithostratigraphy and biostratigraphy of the Waikari and the Mount Brown units and reconstruct the palaeoenvironments and palaeogeography of the Early Miocene in North Canterbury. Field mapping, sedimentary features, and macro and micropalaeontology will be used to along with multivariate analysis of foraminiferal assemblages, to interpret and define palaeoenvironments during the deposition of the Waikari Formation and Mount Brown Beds. Previous work by McCulloch (1981) interpreted fault activated debris flows in the Mount Brown sandstones and limestones, and this will be reassessed.

1.4 Methods

To achieve these aims the main methods included mapping of the Waikari Formation and Mount Brown Beds to define the stratigraphic and geographic distributions. Areas where geological data existed from previous examinations were re-examined when there was a need to resolve problems with data collected that may have conflicted with previous work. Data from Andrews (1968), Edwards et al. (1978) and McCulloch (1981) was further examined to help determine the overall distribution of the Waikari Formation and the Mount Brown Beds.

Stratigraphic columns were constructed from mapping in the Waipara-Waikari area (Appendix 2), samples were collected for analysis and identification of foraminifera. The foraminifera were used to determine the relative stratigraphic age ranges of the Waikari and Mount Brown successions. The stratigraphic and biostratigraphic columns produced were incorporated into a fence diagram to illustrate lateral variation and correlation of biostratigraphic ages that were determined. Macrofossils were also collected to aid in interpreting palaeoenvironment analysis.

Foraminifera species were identified and counted, the data was processed in PAST©; a palaeontological statistical analysis programme. Cluster analysis and Detrended correspondence analysis was used in PAST© to assist in palaeoenvironmental interpretations (Appendix 3). Cluster analysis and Detrended correspondence analysis is discussed further in Chapter 4. Detailed method descriptions will be included in each chapter as required.

Chapter 2

Nomenclature and Descriptions of Waikari Formation and Mount Brown Formation

This chapter will outline the historical nomenclature of the Waikari Formation and the Mount Beds, describe these formations as they occur in the study area and redefine the Mount Brown Beds as the Mount Brown Formation.

2.1 Nomenclature and Terminology History

The names for the Waikari Formation and Mount Brown Beds have undergone a number of amendments in nomenclature since the earliest workers first described these two sequences. Earliest mention of the Mount Brown beds was described as ‘Miocene reddish limestones and white and yellowish sandstone with abundant cup shaped bryozoa’ (Hector 1869). Workers not familiar with the field area could misinterpret a number of outcrops based on the various nomenclature used for both the Waikari Formation and Mount Brown Beds. The Waikari Formation has undergone fewer modifications since Haasts’ description (1871) compared to the Mount Brown Beds.

2.1.1 Waikari Formation Nomenclature

The Waikari Formation, initially was named as the ‘grey marls’ by Haast (1871), are recognised as blue-grey siltstones and brown sandstones. Work by Schofield (1949) in the McDonald Downs District suggested the name ‘grey marls’ needed revising as there were only small areas where the descriptive for the formation was seen in outcrop and that the dominant facies seen were calcareous blue-grey siltstones, brown very fine sandstones rather than marls.

Andrews (1963) first proposed the Waikari Formation, which initially included only 3 members; Pahau Siltstone, Scargill Siltstone and Gowan Hill Sandstone. The basis of the members was compositional differences identified by Andrews (1963). Later examination of the Waikari Formation by Andrews (1968) led to further compositional breakdown of the Waikari Formation and the addition of two more members; Tommy Creek Sandstone and the Glenesk Sandstone (Table 2.1), although these latter two are not seen in the study area.

2.1.2 Mount Brown formation Nomenclature

Nomenclature of the Mount Brown units has previously been described as the Mount Brown Series, Red Crag limestone and the Mount Brown Limestones (Table 2.1). Usage of Mount Brown Beds was derived from the locality of the name, where the limestone beds outcrop prominently. Haast (1877) recognised the Mount Brown Beds and named them the Red Crag Limestones (Table 2.1). In the Mount Brown sequence, Thomson (1920) used the term 'lowest' as a descriptive to refer to the oldest limestone in the sequence, this becomes problematic with the description where 'lowest' was also used to describe the lowest unit seen outcropping at particular exposures. This led to a number of misinterpretations regarding the stratigraphic relationships of the limestones particularly for future workers that were not familiar with the area.

Wilson (1963) attempted further correlation of the Mount Brown Beds and described the main Mount Brown limestones as lower, middle and upper limestones (Table 2.1). McCulloch's (1981) investigation of the Mount Brown succession referred back to nomenclature first introduced by Haast (1877) and referred to the Main Mount Brown beds as Red Crag limestone 1, 2 and 3.

Earliest references to the Whiterock limestone were referred by Haast (1871) and Hector (1877) as the 'bryozoan beds', Thomson (1920) referred to the limestone as horizon 'A'. Work by McCulloch (1981) recognised that the limestone at Claremont Homestead were the same as the exposures of Whiterock limestone seen to the south west and north east of Mount Grey. The outcrop of the limestone at Claremont from where the name 'Claremont limestone' name was derived has been shown to be a fragment of a tectonically displaced fragment of the main limestone unit; the Whiterock limestone (McCulloch 1981).

The Red Crag limestone names were reintroduced by McCulloch (1981) due to a high level of confusion in the use of the term 'Mount Brown'. The use of the term Mount Brown Beds was suggested to be used as a collective term with reference to all limestone units that are in the sequence. The limestones are interbedded with a yellow-brown fine sandstone which has no formal name and has been referred to as 'Altonian Sands' by McCulloch (1981).

Lithology Description	Haast (1871)	Hector (1877)	Thomson (1920)	Wilson (1963)	Andrews (1968)	McCulloch (1981)	Hobbs (2010)	
Yellow-brown sandy, bryozoan and brachiopod limestones and yellow-brown fine calcareous sandstones	Red Crag Limestones	Mount Brown Beds	D C B A	Main Mount Brown Beds Sandhurst Limestone North Dean Limestone Claremont Limestone	Main Mount Brown Beds	Red Crag Limestone 3 Red Crag Limestone 2 Red Crag Limestone 1 North Dean Limestone Whiterock Limestone Altonian Sands	Red Crag Limestone 3 Red Crag Limestone 2 Red Crag Limestone 1 North Dean Limestone Whiterock Limestone Yellow sandstone	**Mount Brown Formation**
Massive, blue-grey calcareous siltstones and brown-grey calcareous	Grey Marls	Grey Marls	Grey Marls	Waikari Formation	Glenesk Sandstone Tommy Creek Sandstone Gowan Hill Sandstone Scargill Siltstone Pahau Siltstone	Waikari Formation	Gowan Hill Sandstone Scargill Siltstone Pahau Siltstone	**Waikari Formation**

Table 2.1 Comparative stratigraphic nomenclature of the Waikari Formation and Mount Brown Beds.

2.1.3 Nomenclature in Current Study

The nomenclature used by Andrews (1963, 1967) and McCulloch (1981) for individual members of the Waikari Formation are retained and used where relevant in the study (Table 2.1). Within the geographical area covered in this present study only three out of the five members were relevant in this study; Pahau Siltstone, Scargill Sandstone and the Gowan Hill Sandstone (Table 2.1).

Where the practicable the nomenclature for the Mount Brown units, by Wilson (1963) and McCulloch (1981) are used for the Mount Brown units (Table 2.1). Nomenclature for the Whiterock Limestone is used in this study as it takes precedence over ‘Claremont’ as the date of formal publication (Mason 1941) precedes the other by more than 20 years. The Whiterock is also better established in general usage.

In this study, Red Crag Limestone 1 and 2 will be used to refer to the uppermost escarpment forming limestone that is seen along most of the extent of Deans Range and Mount Brown (Fig. 3). The term Mount Brown Formation will be used as a collective term for all the limestone units in its sequence, and the interbedded yellow-brown fine sands.

The basis for the use of Red Crag limestone are:

1. Red Crag was introduced before ‘Mount Brown’ (Table 2.1).
2. Descriptions of the unit are more appropriate as Red Crag limestone (McCulloch 1981).
3. Stratigraphic misinterpretations caused by further subdivision of lower, middle and upper (Wilson 1963).

The term Mount Brown Formation will be used and represent the sequence of sandstones, limestone. This will include the Yellow sandstone, previously known as ‘Altonian Sands’, the Whiterock Limestone, Onepunga Shell Beds, North Dean Limestone and Red Crag Limestones 1, 2 and 3.

2.2 Waikari Formation Descriptions

The Waikari Formation consists of blue grey siltstones and brown fine sandstones observed in the Waipara and Waikari area. The members seen in the study area included the Pahau Siltstone, Scargill Siltstone and the Gowan Hill Sandstone (Fig. 4). The Waikari Formation is widespread throughout the North Canterbury region and outcrops were seen frequently throughout the area (Fig. 3). Areas where the Waikari Formation was measured include Onepunga, roadside section at Mount Brown, the Waipara River, lower slopes of the Deans Range, Karetu Downs (south branch Waipara River) and McDonald Downs as seen in Figure 5.

Three members were recognised that correlate with the Waikari Formation; the Pahau Siltstone, Scargill Siltstone and the Gowan Hill sandstone (Figure 4 and 5). The Glenesk Sandstone and Tommy Creek Concretionary Sandstone identified by Andrews (1968) that are also included in the Waikari Formation were outside of this study area.

2.2.1 Pahau Siltstone

A. Distribution

The Pahau Siltstone covers the western and north eastern parts of the Waipara-Waikari region, in the study area it was identified at Karetu Downs on the western and eastern limbs of the McDonald Syncline, conformably overlying the Weka Pass Limestone (Fig.3). Andrews (1968) also recognised it in the western and north eastern parts of the Waipara – Waikari region. This study did not extend as far as earlier studies by Andrews (1960, 1963 and 1968).

B. Thickness

The Pahau Siltstone ranged in thickness from 6m at the Waipara river section to 31m on the eastern and western limb of the McDonald Syncline.

C. Description

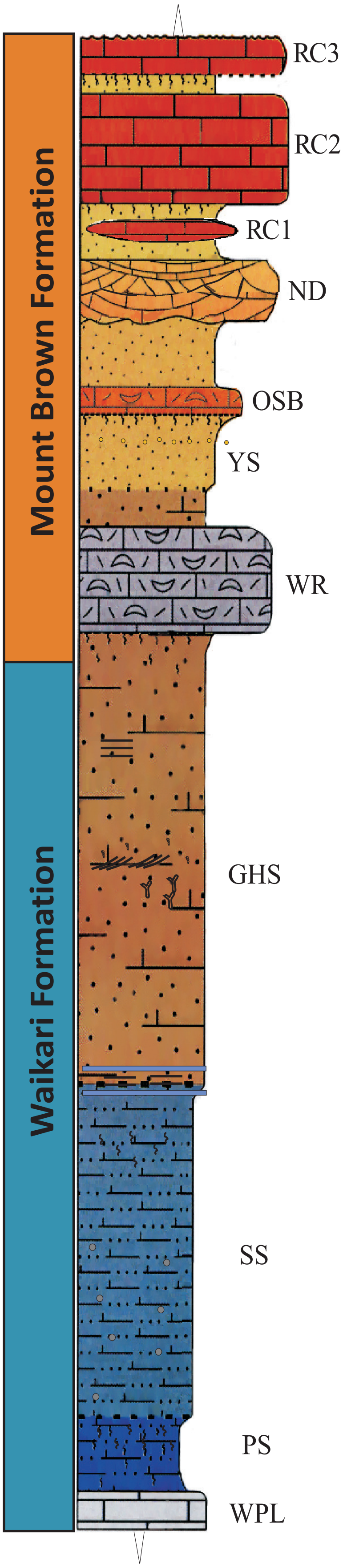
The Pahau Siltstone is highly glauconitic, grey-green, poorly sorted, massive, calcareous sandy siltstone, conformably overlying the Weka Pass limestone. The sediment is high in glauconite, quartz and feldspar, with minor amounts of mica. The clasts are subangular to subrounded, coarse silt to very fine sand and are lithified to form moderately indurated rocks.

The Pahau Siltstone consists of sandy siltstone and sandy mudstones. Terrigenous content of the siltstone was quartz, micas, foraminifera and minor amounts of shell fragments (bivalves and brachiopods). Qualitative analysis of samples from the sections found that the glauconite content range from c. 10 – 30%. The high glauconite content distinguishes the Pahau Siltstone from the Scargill. The glauconite is dark green and well rounded, indicating reworking of the grains.

In outcrop the Pahau Siltstone was massive in nature, with moderate to heavy bioturbation by the trace fossil; *Ophiomorpha* and *Zoophycos*, particularly in lower sections of the Pahau Siltstone at Karetu Downs (Fig 4 and 5). *Zoophycos* are typically found at mid shelf to slope water depths, in moderately stable environments (Wetzel 1992; Goldring 1993). *Zoophycos* has been found to correspond to the continental slope (Gaillard and Rachebouef 2006), but is also found on the shelf in combination with other trace fossils like *Ophiomorpha*. *Ophiomorpha* are found at mid shelf to outer shelf water depths.

D. Macrofossils

There were no macrofossils that were able to be identified in the Pahau siltstone. On the eastern limb of the McDonald Syncline microfossil samples were collected and used for the correlation of relative stratigraphic ages, and interpretation of environments. This microfossil work is described in chapters 3 and 4.



RED CRAG LIMESTONE (RC)

Yellow-brown, fine to very coarse sand, poorly sorted, moderate-well indurated, massive limestone. Consists of three main units Red Crag 1(RC1), Red Crag 2 (RC2) and Red Crag 3 (RC3); that are the same composition but have different fauna. Red Crag 1 occurs intermittently as lenses. Red Crag 2 has a high abundance of brachiopod fauna. Red Crag 3 has more molluscan fauna.
Red Crag 3 up to 10m. Thicknesses: RC1 Red Crag 2

NORTH DEAN LIMESTONE (ND)

Yellow-brown, fine to coarse sand, moderate-well sorted, well indurated, crossbedded limestone. Often seen directly underlying Red Crag Limestone 2 in areas. Thickness of unit up to 20m.

ONEPUNGA SHELL BEDS (OSB)

Yellow-brown, fine calcareous sand, well indurated, moderately sorted, massive sandy limestone. Characterised by molluscan shell casts. Interbedded with the Yellow sandstone, sandstone clasts near base of the limestone. Thickness up to 2.5m.

WHITEROCK LIMESTONE (WR)

Grey-cream, medium to coarse calcareous sand, moderately indurated, bryozoan dominated, massive, limestone. Characterised by the presence of *Celleporaria* and branching bryozoans. Thickness up to 30m.

YELLOW MT BROWN SANDSTONE (YS)

Yellow-brown, very fine to fine calcareous sand, moderate-well sorted, moderately indurated, massive sandstone. Three members of limestone interbedded (Onepunga Shell Beds, North Dean Limestone and Red Crag Limestone). Laminated towards the top of sandstones locally. Mid shelf species of macrofauna and foraminifera. Becomes bioturbated by *Ophiomorpha* near the bases of limestone members.

GOWAN HILL SANDSTONE (GHS)

Alternating beds of Yellow-grey brown, calcareous, very fine to fine calcareous sand, moderately sorted to well sorted, massive, sandstone and Light blue-grey, calcareous, calcareous coarse silt, moderately sorted, moderately indurated, massive sandy siltstone.
Increase in faunal components predominantly mid shelf species including; bryozoan fragments, brachiopods and cetacean bones. Thickness of unit up to 286m.

SCARGILL SILTSTONE (SS)

Light blue-grey, coarse silt to very fine sand, moderate to poorly sorted, massive, calcareous sandy siltstone. Consists of indistinct bedding of slightly coarser sediment. Concretions distributed sparsely through the siltstone. Bioturbated predominantly by *Ophiomorpha.* Increase in faunal material mid to outer shelf species. Thickness of the units is up to 235.5m.

PAHAU SILTSTONE (PS)

Glauconitic, blue grey-green, coarse silt, poorly sorted, bioturbated, massive, calcareous siltstone. Heavily bioturbated by *Zoophycos.*
Thickness of unit up to 31m.

WEKA PASS LIMESTONE (WPL)

Figure 4. Generalised Stratigraphic column of the Waikari Fomation and Mount Brown Formation

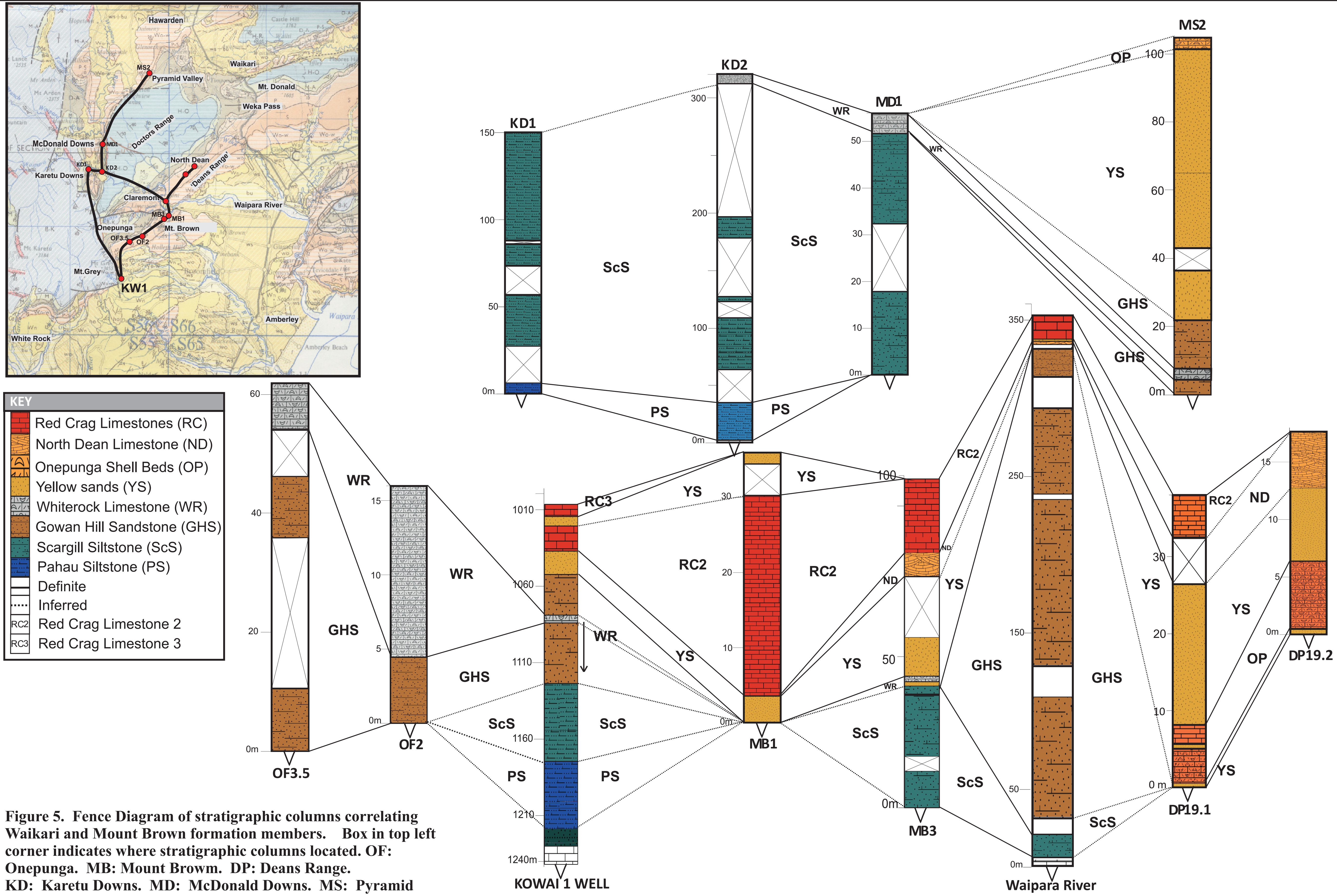


Figure 5. Fence Diagram of stratigraphic columns correlating Waikari and Mount Brown formation members. Box in top left corner indicates where stratigraphic columns located. OF: Onepunga. MB: Mount Browm. DP: Deans Range. KD: Karetu Downs. MD: McDonald Downs. MS: Pyramid Valley. Kw1: Kowai 1 Well. Kowai 1 Well was modified from Edwards et al. (1978) and McCulloch (1981).

2.2.2 Scargill Siltstone

A. Distribution

The Scargill Siltstone overlies the Pahau Siltstone and is seen in the north western to the east coast of the North Canterbury region (Andrews 1968). Within the study area the Scargill Siltstone is observed in the Waipara River, along the lower parts at the south eastern end of 'Deans Range', Mount Brown and Karetu Downs (Fig. 3 and 5).

B. Thickness

The thickness of the Scargill Siltstone ranges from 14 – 235.5m. The thickest measurements of the Scargill Siltstone occurred in the Karetu Downs area in the McDonald Syncline on the eastern limb (235.5m) and the western limb (137.7m). To the north west of Karetu Downs at McDonald Downs the Scargill Siltstone measured was 47.2m thick. The Waipara River section measured 12.9m. On the side of the road at Mount Brown the section measured was 14m. Previous work by Andrews (1963) found that the Scargill Siltstone was thicker to the southwest and thins out toward the north east, outside of the study area.

C. Description

The Scargill Siltstone overlies the Pahau Siltstone, with a gradational contact. The Scargill Siltstone is a moderately indurated, light blue-grey, calcareous, sandy siltstone. When in outcrop the sediment is massive, with indistinct bedding of slightly coarser material, which was reflected in the weathering pattern. Sections where the Scargill Siltstone was measured in the study was Karetu Downs, Waipara River, McDonald Downs, Pyramid Valley and a road cutting on the side of Mount Brown (Fig.5).

Qualitative analysis of the samples examined found the sediment consisted of foraminifera, quartz, feldspar, glauconite, mica and bivalve shell fragments. The glauconite content is c. 5 – 10% considerably lower than underlying the Pahau Siltstone. The grains are dominantly coarse silt to fine sand, are subangular to subrounded, poorly sorted and enclosed in a coarse, silty, calcareous matrix. Sedimentary structures are not preserved in the Scargill Siltstone; however bioturbation is at moderate to high levels and may have obliterated the any original structures.

Concretions 1 – 2.5cm in diameter are distributed sparsely throughout the Scargill Siltstone. At the McDonald Downs section they appear to have developed around worm burrowes.

Sections where the Scargill Siltstone was identified and measured was Karetu Downs and middle branch Waipara River. Two sections were measured at Karetu Downs (Fig. 5), Waipara River and these were the most complete sections observed for the Scargill Siltstone in the study (see Appendix 2). The Scargill Siltstone overlies the Pahau Siltstone and is best recognised by the change in grain size and the glauconite content.

D. Macrofossils

The macrofossil content is lower compared to the overlying Gowan Hill Sandstone (discussed in section 2.2.3). Many of the macrofossils are fragmented and very fragile making extraction and identification of species difficult. The western limb of the McDonald Syncline contained more macrofossil fragments compared to the eastern limb of the McDonald Syncline.

Macrofossils seen in the Scargill Siltstone include; bivalves (*Lentipecten hochstetteri*), gastropods, fragmented brachiopods (possibly Terebratulid), fenestrate bryozoa, worm tubes, fragmented scaphopods and branching bryozoa.

The macrofossils seen on the western limb of the McDonald Syncline included bivalves and fenestrate bryozoa. The bivalve *Lentipecten hochstetteri* was identified on the western limb of the McDonald Syncline. The Mount Brown, Karetu Downs and MacDonald Downs sections have increase in the fossil content toward the top of the sections (Appendix 2).

Trace fossils observed in the Scargill Siltstone include; *Ophiomorpha* and *Zoophycos.* The intensity of bioturbation was heavy near the base of the Scargill Siltstone, moderate through the middle sections, followed by an increase in bioturbation again toward the top of the Scargill Siltstone.

Ophiomorpha are found from inner to outer shelf water depths in loose sandy sediments (Woods and Hansen 1985, Ekdale and Lewis 1990; Zonneveld et al. 2001). Both these traces are identified in the Scargill Siltstone, the dominant trace was *Ophiomorpha* compared to *Zoophycos* indicating mid shelf to upper outer shelf water depths and below wave base in calm conditions.

2.2.3 Gowan Hill Sandstone

A. Distribution

The Gowan Hill Sandstone occurs in a band in the central west region in the Waipara – Waikari region in the study and gradationally overlies the Scargill Siltstone. The Gowan Hill Sandstone was recognised in the Waipara River, Onepunga and 'Deans Range' (Fig. 5)

B. Thickness

The Gowan Hill Sandstone at Onepunga has a measured thickness of 53.3m. The thickness at the Waipara River section was 286.6m thick (Fig 3.), this was the most complete section measured. The unit consists of yellow-brown, calcareous, massive sandstone, and light blue-grey, calcareous, massive, sandy siltstone. At the Waipara River the sandstone beds were 20cm – 15m thick, while the alternating siltstone seen at the Waipara River were 25cm – 1m thick.

C. Description

The sandstone consists of alternating beds of yellow – grey brown, calcareous, massive, silty sandstone and light blue – grey, calcareous, massive, sandy siltstone (Fig. 4). The yellow-brown sandstones range from 1-5m thick with alternating bands of the light blue-grey siltstone, which ranges from 20cm – 35m thick.

Terrigenous material is dominated by quartz and feldspar, some ferromagnesium minerals and micas (muscovite and biotite). The fossil content of the Gowan Hill Sandstone is distinguished by the presence of bryozoan fragments. Other common components included foraminifera, molluscan shell fragments and glauconite.

The sands ranged from moderately well sorted to poorly sorted. The glauconite content of the sandstone was lower than both the Pahau Siltstone and the Scargill Siltstone based on qualitative assessments the glauconite content was c. 3 – 5%.

The key section measured which showed all the Gowan Hill Sandstone was at the Waipara River (Fig. 5 and Appendix 2). Most places where the Gowan Hill Sandstone is exposed, the sandstone beds are typically massive and non-graded. The massive sandstone beds are caused by low to high levels of bioturbation caused by *Ophiomorpha* and *Zoophycos.*

In the Gowan Hill Sandstone, light blue grey siltstones are interbedded in the lower sections of the unit. The light blue-grey siltstones were common in lower sections of the Gowan Hill Sandstone. Sedimentary structures observed in some localities of the sandstones; include faint laminations, crossbedding and hummocky cross stratification. These sedimentary structures occurred toward the middle of the Gowan Hill Sandstone.

Faint laminations occur intermittingly up through the Gowan Hill Sandstone, in the lower section of the sandstone the laminations occur with siltstone clasts that have been ripped up from an underlying siltstone bed (Fig. 6). The blue-grey siltstone clasts seen in Figure 6 are ramping over each other, indicating traction currents ripping up the siltstone causing soft sediment deformation. Andrews (1968) suggests that soft sediment deformation was occurring during the accumulation of the Gowan Hill Sandstone.

Figure 6. Gowan Hill Sandstone showing siltstone clasts in faintly laminated sandstone bed that has been ripped up from underlying blue-grey siltstone.

The two localities in the Waipara River section where hummocky cross-stratification is observed are in the middle to upper sections of the Gowan Hill Sandstone (Appendix 2). At both locations fossil material was observed as discontinuous horizons. The actual fossil content varied at both these locations and will be discussed in the next section. Hummocky cross-stratification is recognised to have been caused by storm events, where there is increased wave action below fair weather wave base (Walker 1985; Vossler and Pemberton 1988b, 1989; Frey 1990). When fauna is present on the seafloor during these storm events they can be transported further down the shelf.

Thirty metres stratigraphically up from the hummocky-cross stratification in the Waipara River section there is a large broad channel. Distinguishing the channel is difficult, based on slight compositional of the channel infill. The channel contained fragments of carbonaceous material and higher amounts of macrofossils.

D. Macrofossils

Many of the macrofossils identified were moderately to well preserved. In the light-grey silty sandstone the macrofossils seen in the beds included; brachiopods, bivalves (*Lentipecten* *hochstetteri, Serripecten hutchinsoni, Pecten n. sp*), fenestrate bryozoa, echinoid spines and plates, encrusting bryozoa, *Ostrea, Flabellum* coral and cetacean vertebra. In the yellow-grey brown sandstones macrofossils in these beds included brachiopods, fenestrate bryozoa, *Balanus*, branching bryozoa and echinoid plates.

Branching bryozoa, fenestrate bryozoa were found in moderate abundance but were highly fragmented (Fig.7). These are the discontinuous horizons that are related to the hummocky cross-stratification. The horizon was 65cm thick, contains around 70% bioclastic fragments. The fragmented and poorly sorted nature of the horizon indicates a storm event that has transported the bryozoans further down shelf.

The channel mentioned in previous section included; horizons of Terebratulid brachiopods (Fig. 8A and B), encrusting bryozoan (Fig. 8C) cetacean vertebra (Fig.8D), and fenestrate bryozoa (Fig.8E) and trace fossils such as *Rosselia*? (Fig.8F) and *Ophiomorpha* (Fig.8G). The encrusting bryozoa are seen attached to brachiopod valves. A number of the brachiopods had carbonaceous material around the valves, fenestrate bryozoa were also seen to have the carbonaceous material trapped.

Figure 7. Discontinuous horizon of branching bryozoa in the Gowan Hill Sandstone at Waipara River.

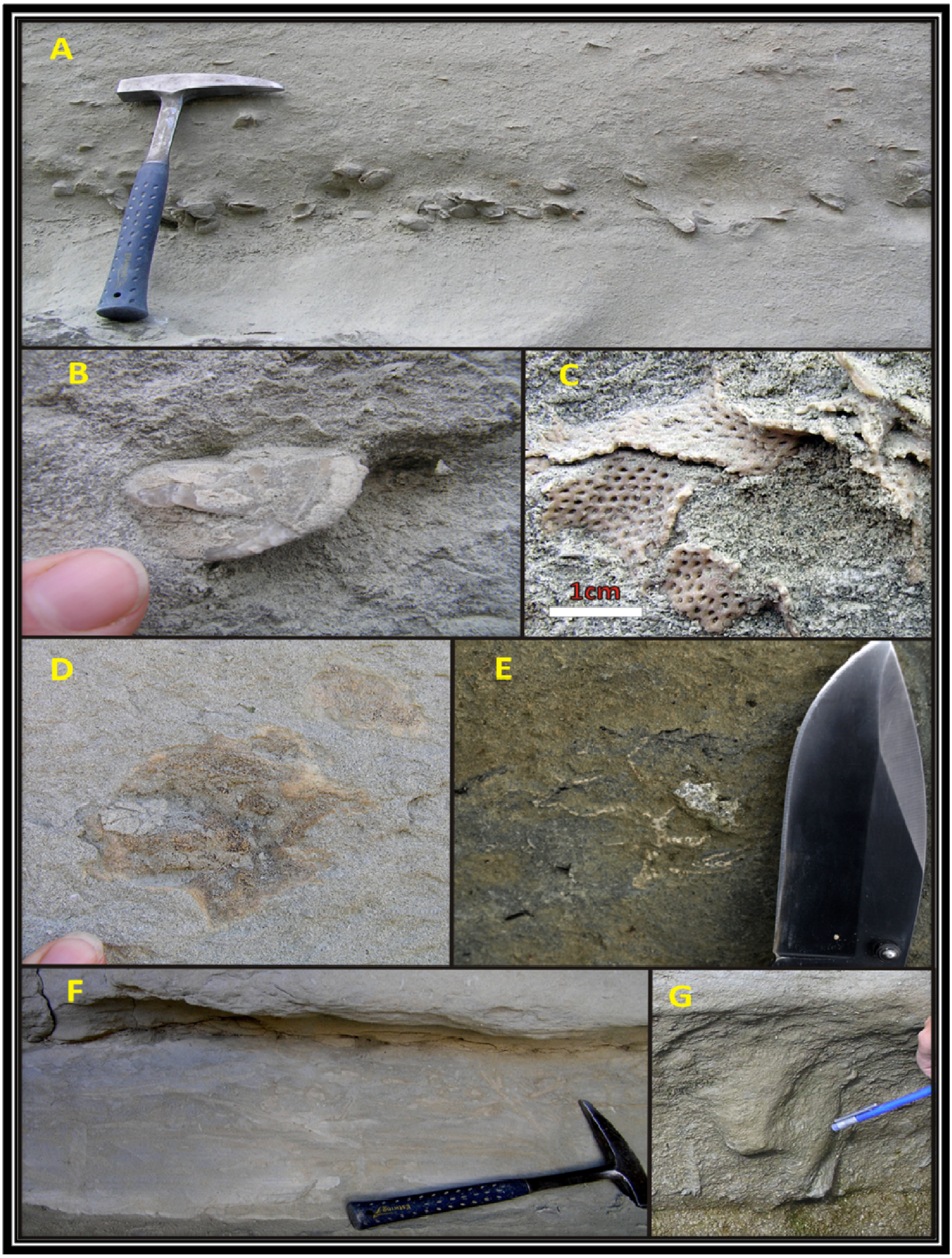


Figure 8. Macrofossils and tracefossils found in the Gowan Hill Sandstone. A: Brachiopod horizon in channel. B: Encrusting bryozoan attached to brachiopod valve. C: Fenestrate bryozoa. D: Cetacean vertebra. E: Fenestrate bryozoan with carbonaceous material beside it. F: *Ophiomorpha* traces G: *Rossellia*? (sea anemone). Hammer length 33cm, knife blade length 10cm.

2.3 Mount Brown Formation

The Mount Brown Formation is defined as the yellow sandstones and limestones between the Waikari and Kowai formations, which outcrop along the north western face of the Deans Range. No single complete type section exists in outcrop and the concept of the Mount Brown Formation is developed from multiple sections. The section begins in the Waipara River and extends to the top of the southwestern extent of the Deans Range. The Whiterock Limestone is best exposed at Onepunga Farm (Fig. 5).

The 4 limestone members include; Whiterock Limestone, Onepunga Shell Beds, North Dean Limestone and the Red Crag Limestone (1, 2 and 3) as seen in Figure 4. The Whiterock limestone a creamy-whitish bryozoan rich limestone; the Onepunga Shell Beds are a brown sandy limestone; the North Dean Limestone is a yellow-brown quartz rich sandy limestone; the Red Crag limestones consist of a yellow-brown, sandy bioclastic limestone. Stratigraphic columns were measured at Onepunga, Mount Brown, Waipara River, Deans Range, Waipara River, MacDonald Downs, Karetu Downs and Pyramid Valley and are included in Figure 5.

2.3.1 Yellow sandstone

A. Distribution

The yellow sandstone is seen from the southwestern end of Mount Brown, the outcrops occur sporadically in areas on the western side of Mount Brown. At Waipara River the sandstone is seen lying between Red Crag Limestone 2 and Red Limestone Crag 3 (Figure 4 and 5). Along the Deans Range the sandstone exposures are seen intermittently extending along the western slopes and in gullies on the eastern side. The sandstone is seen extending further to the north east into Weka Pass on the eastern slopes of Mount Donald.

B. Thickness

The thicknesses ranged from 1.5 – 35m. The thickest areas where the sandstone was measured at 35m was on the Deans Range and on Mount Brown the thickest section of the sandstone measured was 31m. The thickness of the yellow sandstone could be greater than at the sections measured; as the sandstone is separated by limestone members; the upper and lower contacts were unable to be established. Further north east of the study area the sandstone may be thicker. The yellow sandstone was not as prominent at the north eastern end of Mount Brown where the thickest exposures of the Red Crag Limestones are seen.

C. Description

These yellow sandstones are yellow-brown, moderately to poorly indurated, very fine to fine sand, moderate to well sorted, calcarenite. In outcrop the sandstone appears bedded (Fig. 9A). Sedimentary structures seen in the sandstone include laminations and small cross beds. In some sections in outcrop the sandstone appears massive. The sections that appeared massive increased levels of bioturbation which may have removed any internal structures. The sandstone consisted of quartz grains that are subangular to subrounded, glauconite (subrounded), mica and bioclastic material. The glauconite content ranged from c.1 – 5%.

Mud drapes are seen on Mount Brown and south of North Dean on the Deans Range. The mud drapes were small and discontinuous. In the sections where the mud drapes were observed were laminations and small pockets of fragmented bioclastic material (barnacles and bivalve shell fragments). The mud drapes are not seen continuously throughout the yellow sandstones; indicating periods of higher wave action further up the shelf, the mud was transported down the shelf and deposited as current energy waned.

D. Macrofossils

The macrofossils identified in the yellow sandstones were barnacles (*Balanus*), fenestrate bryozoa, *Ostrea*, encrusting bryozoa, fragments of *Pecten*, fragments of brachiopods, *Lentipecten hochstetteri* and gastropods (mostly fragmented). The most common macrofossil seen in the yellow sandstones was the barnacle *Balanus*. On Mount Brown they are seen in moderate numbers and along the Deans Range are seen more prominently. Barnacles are filter feeders they typically inhabit hard substrates where there are rocks or other shells on the seafloor which has strong currents keeping the bottom relatively free of terrigenous sediment (Kamp et al. 1988; Beu et al 1980).

E. Ichnofacies

Tracefossils were identified throughout the yellow sandstones and bioturbation levels increased toward the top of beds when they were seen outcropping with the interbedded limestones. The most common trace fossil identified was *Ophiomorpha* (Fig 9B and C). The other trace fossils included *Thallasinoides* (Fig.9D) and *Planolites* (Fig.9E and F).

Ophiomorpha are found at inner to mid shelf water depths, typically in beach deposits consisting of well sorted, fine to very fine grained sands (Woods and Hansen 1985). *Planolites* are found in similar facies when present in low numbers (Woods and Hansen 1985; Ekdale and Lewis 1990;

Zonneveld et al. 2001). Water depths of *Planolites* extend down from shelf to slope depths (Pemberton and MacEachern 2005).

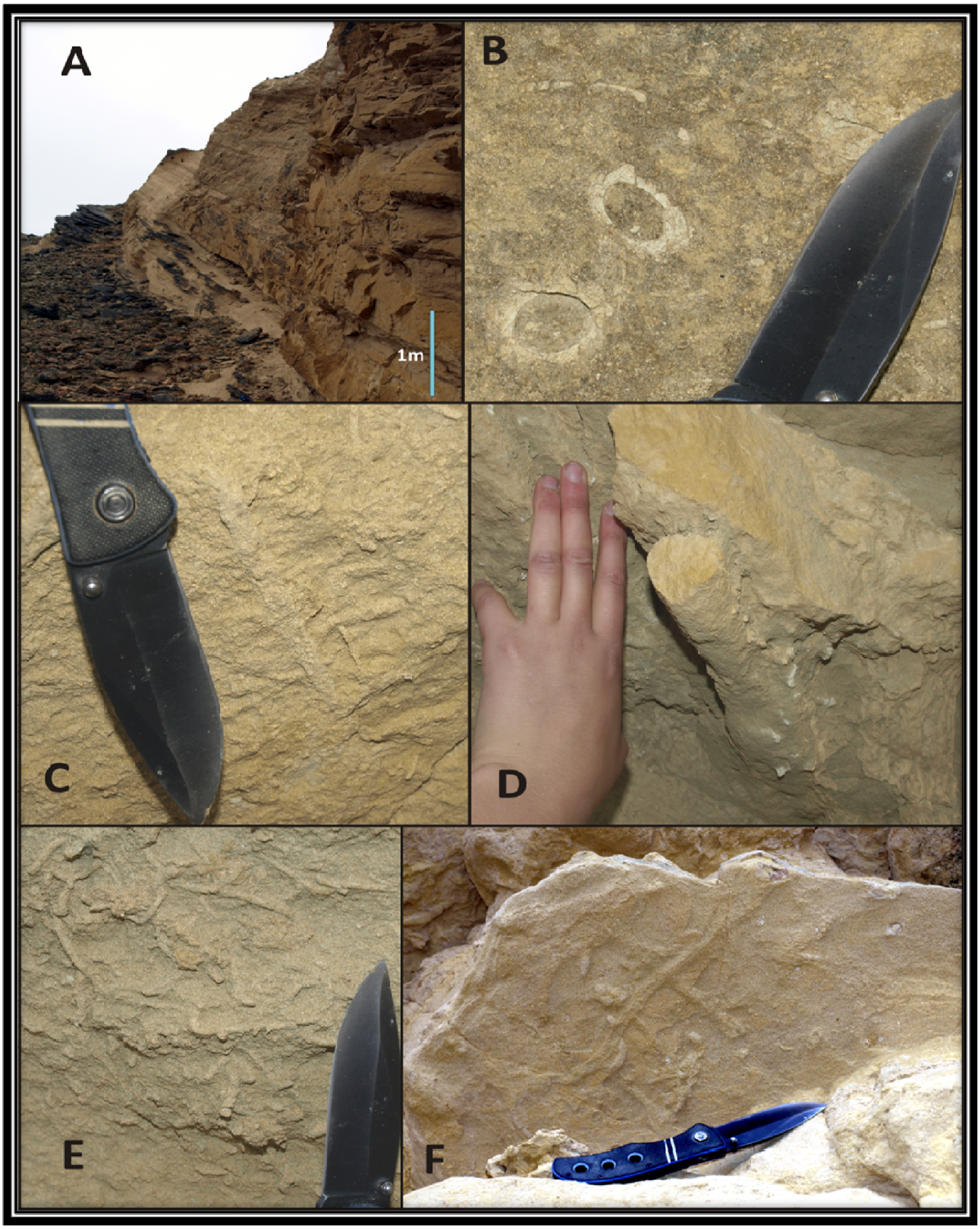


Figure 9. Trace fossils from the Yellow sandstone, in the Mount Brown Formation. A: Bedding seen in outcrop. B: *Ophiomorpha* traces. C: *Ophiomorpha* traces. D. *Thallasinoides* trace. E: *Planolites* traces. F: *Planolites* trace on the bottom of a bed. Length of knife 20cm.

2.3.2 Whiterock Limestone

A. Distribution

The Whiterock Limestone is distinctly cream-yellow to whitish in outcrop and can be seen extending along escarpments at Onepunga Farm, until it is truncated and offset by the Boby Creek Fault (Fig. 3). The exposure of the limestone is discontinuous along the slopes of Mount Brown, until it is seen clearly again at Claremont homestead, some 5km away to the north east where it outcrops in the front paddock. The Whiterock limestone is then seen in the south and middle branch of the Waipara River.

Sections where this limestone were examined include; Onepunga, Mount Brown, Claremont Homestead, Karetu Downs and McDonald Downs (Fig. 5). Other localities that were investigated by McCulloch (1981) are at Okuku River and Whiterock Quarry.

The Whiterock limestone shows a threefold differential weathering profile seen at Onepunga Farm. The lower and upper levels are more indurated and the middle level is more porous and friable, which leads to it are weathering out more readily compared to the lower and upper level. This weathering pattern was observed by McCulloch (1981) at Whiterock Quarry and at Onepunga. Investigation to the north west in Waikari at Karetu Downs and McDonald Downs identified the lower level.

B. Thickness

The limestone is thickest to the southwest at Whiterock quarry (McCulloch 1981; Field and Browne 1985) and the limestone thins to the north west up to Pyramid Valley (Fig. 5). The thickness of the Whiterock limestone measured in this study ranged from 2 – 16m thick. Sections where the Whiterock limestone was measured were Onepunga, Mount Brown, Claremont Homestead, Karetu Downs, MacDonald Downs and Pyramid Valley. Two localities to the south of the study area; Whiterock quarry has a thickness of 30m, at Okuku River a thickness of 13m (McCulloch 1981).

The sections measured at Onepunga property had a minimum thickness of 2m and a maximum thickness of 16m. At Claremont homestead the outcrop observed in the front paddock of the property was 5m thick. The thickness measured at Mount Brown (Section MB3) was 2.2m thick. The limestone that was exposed at Karetu Downs in the south branch of the Waipara River was 5.5m thick. At McDonald Downs the thickness of the Whiterock Limestone was 4.1m.

C. Description

The Whiterock Limestone is a grey – cream, moderately to poorly indurated, poorly sorted, sandy calcarenite, bryozoan biosparite. In outcrop the limestone appears massive; no sedimentary structures were seen at Onepunga, Claremont Homestead, Karetu Downs and McDonald Downs. McCulloch (1981) added that the lowest limestone unit examined in the Kowai I well resembled the lower sections of the Whiterock limestone. Mason (1941) found the Whiterock limestone to be "distinctly current-bedded in places"; this was not seen at any of localities in this study or in the previous study by McCulloch (1981).

Terrigenous content in the limestone include fine quartz sand grains that are subrounded to subangular. The range of quartz grains varied from c. 6 – 30%. The carbonate content of the limestone ranged from c. 60 – 80%, the levels of carbonate in the lower and middle sections of the limestone were typically lower compared to the middle section. An area where the carbonate content was highest was in the bryozoan horizon in the middle section of the limestone at Onepunga (Appendix 2).

Faunal components include bryozoa, bivalve and brachiopod shell fragments, foraminifera and solitary corals. Many of the faunal fragments are unworn and had not been transported a great distance to any extent.

D. Macrofossils

The Whiterock Limestone is characterised by the abundance of fossils that are within the limestone. Six phyla are represented in the limestone; bryozoa is the most abundant both as to diversity and abundance. Brachiopods were the next prominent group, molluscs, echinoderms, coral and foraminifera (discussed further in Chapter 3 and 4).

Bryozoa are a complex and diverse group which leads to problems with systematic identification of species (Amini et al. 2004). The various morphotypes (growth forms) that are observed in bryozoans are useful for palaeoenvironmental information (Nelson et al. 1988). In this study the morphotypes of bryozoa were used as palaeoenvironmental and palaeoecological indicators.

The characteristic of this limestone is the presence of the cupuliform bryozoa, *Celleporaria papillosa* which is abundant in the middle section of the limestone (Fig.10). These are abundant in the middle section of the Whiterock Limestone, the lower and upper level also contained the *Celleporaria papillosa* but were not as abundant. Modern *Celleporaria* species in New Zealand are found in water depths that range from 68 - 690m with a mean depth of 214m (Taylor et al.

2004). Moisette et al (2007) found these bryozoan forms are found on sandy and shelly bottoms at depths of 30 – 60m in modern environments.

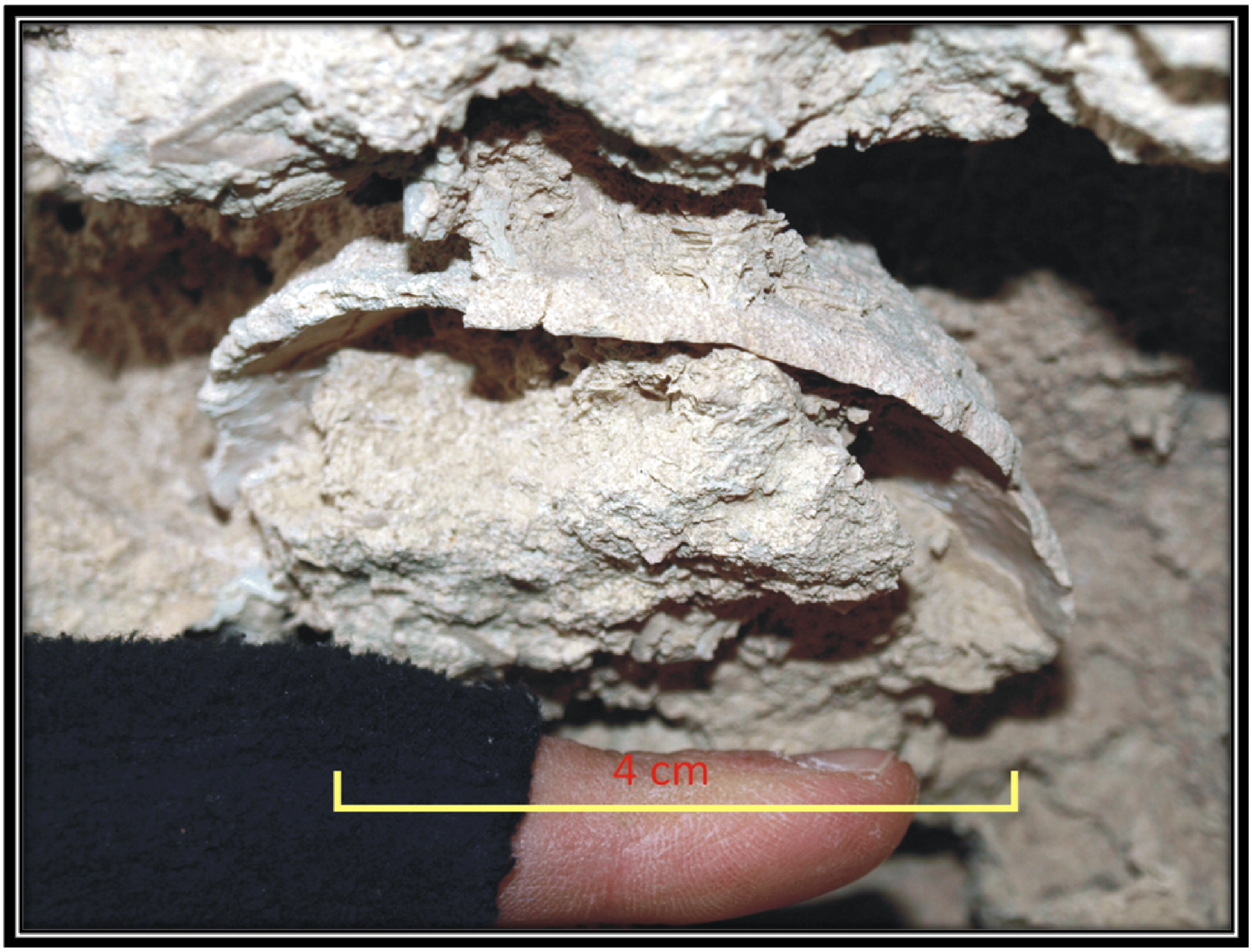


Figure 10. Image of *Celleporaria papillosa* from outcrop at Onepunga.

Other forms of bryozoans that are prominent in the Whiterock Limestone include branching (Fig. 11A, B), fenestrate (Fig. 11C) and encrusting bryozoan symbionts (Fig. 11D). There were also encrusting bryozoa that were attached on brachiopods. The branching bryozoa were prominent in the middle section of the Whiterock Limestone at Onepunga and were less fragmented. They were also present in the upper and lower sections but were more fragmented. Fenestrate bryozoa were observed in low to moderate amounts, from the lower to upper sections of the Whiterock Limestone.

There were two brachiopods identified, from the genus *Magadina* and *Pachymagus*. *Magadina* was the least abundant of the two brachiopods and were typically found in the lower sections of the limestone. *Pachymagus* was seen in the middle and upper sections of the limestone in larger numbers after the bryozoans. Much of the molluscan material was moderate to highly fragmented and species included *Serripecten hutchinsoni*, *Lentipecten hutchinsoni*, *Pecten spp.*

and gastropods that were unable to be identified. Echinoderm plates and spines were observed in the Whiterock Limestone and were highly fragmented making identification difficult.

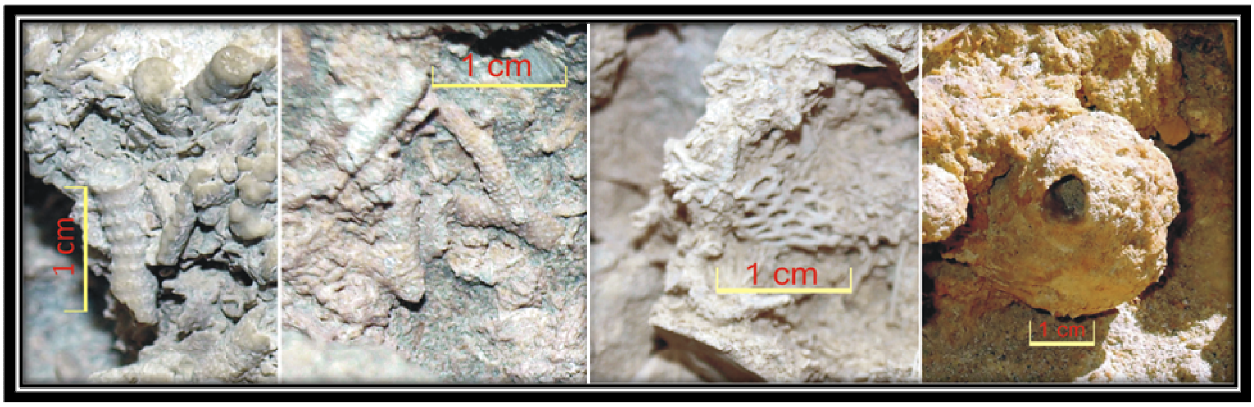


Figure 11. Various bryozoans in the Whiterock limestone. A – D were identified at Onepunga, D was identified on Mount Brown. A and B are branching bryozoans found at Onepunga. C: A fenestrate bryozoan located at Onepunga; D: tube building bryozoan symbionts located at Mount Brown.

E. <u>Ichnofacies</u>

There were a number of trace fossils observed in the Whiterock Limestone that are useful for palaeoenvironmental reconstructions. The trace fossils observed in the Whiterock Limestone include; *Ophiomorpha* and *Pisichnus* a ray feeding trace (Fig. 12). *Ophiomorpha* are noticeable in moderate levels in the lower and mid sections with a decrease in the upper levels of the limestone. The *Pisichnus* was not common in the limestone and was seen in the upper levels of the limestone.

Pisichnus is a feeding trace that has been preserved when a ray excavates into soft sediment on the sea floor in search of food. In the rock record distinguishing features of *Pisichnus* can include; coarse and poorly sorted infill, more than 10cm in diameter and a bowl shaped outline. Optimal preservation and identification of these traces are when the excavations have been infilled by sediment of a marked textural contrast (Gregory 1991).

Gregory (1991) noted that ray traces can be found in a range of water depths and in various facies types; in sandier facies they are typically associated with shallow water, moderate to high energy environments.

Figure 12. Ray feeding trace in the lower section of the Whiterock limestone at Onepunga. Bowl shaped outline with coarser material (branching bryozoa) and sandstone infilling the bowl. The rock hammer was used for scale.

2.3.3 Onepunga Shell Beds

A. Distribution

The unit is named for the type locality, where it is best observed, north east of Mount Grey on the Onepunga property. Wilson (1963) included the Onepunga Shell Beds with the North Dean Limestone. McCulloch (1981) described the Onepunga Shell Beds as an individual limestone as it is described here in this study.

The Onepunga Shell Beds appear as individual lenses in the Waipara-Waikari region (Fig. 4). Exposures of the shell beds are seen at Onepunga, no exposures of the shell beds are seen along the western slopes of Mount Brown. The beds then occur discontinuously along the western slopes of Deans Range and are seen in Pyramid Valley (Fig. 5).

The outcrop character of the shell beds is typically a yellow-grey massive sandy limestone, made up of abundant casts of bivalves and gastropods as seen in Figure 13.

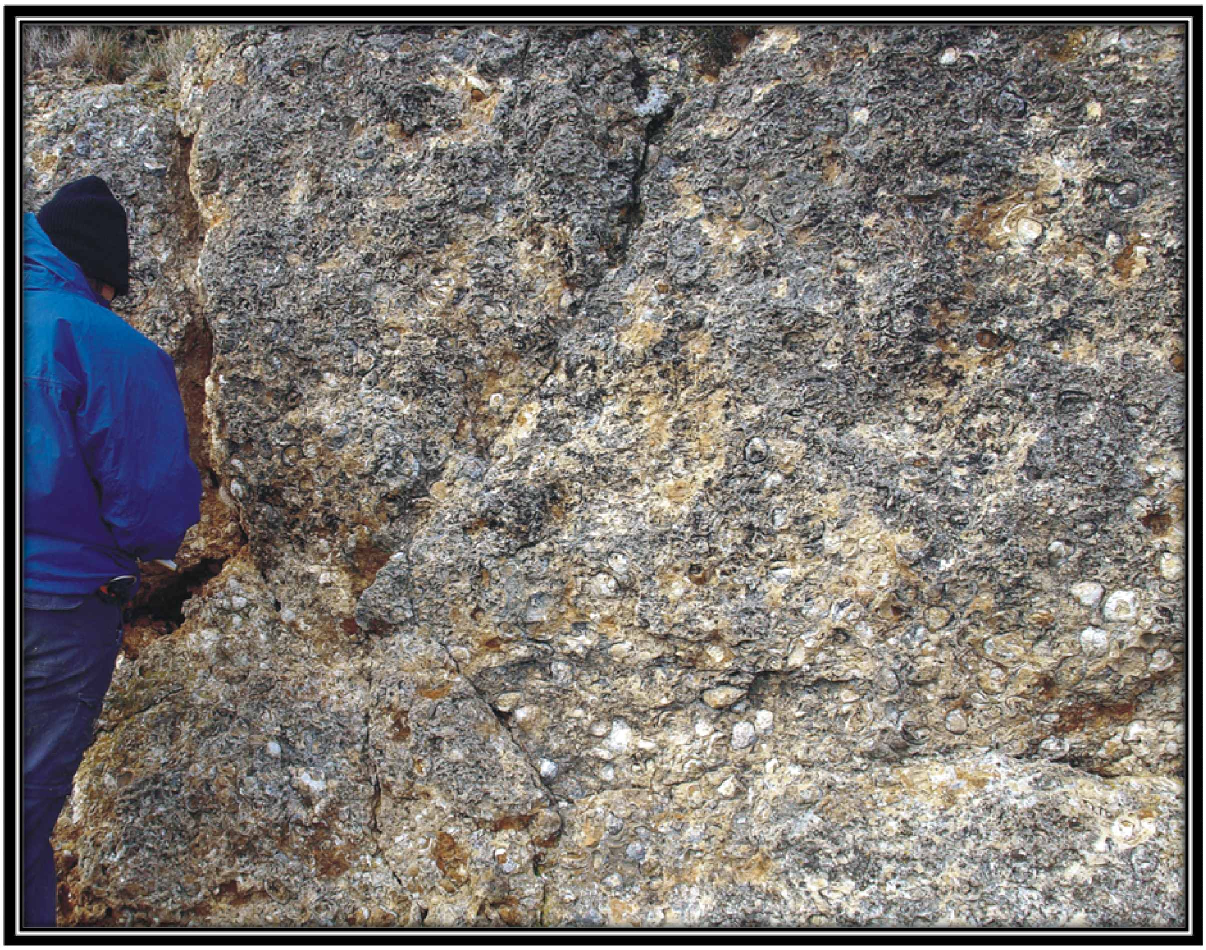


Figure 13. Typical outcrop characteristic of the Onepunga Shell Beds. Photo was taken at Pyramid Valley (MS1).

B. Thickness

The Onepunga Shell Beds were measured at four locations (Fig. 5); thicknesses ranged from 1.3m – 3m. The locations included to the south east of Onepunga (Onepunga – Holleth Hills), two sections to the north east along Deans Range (DP19.1 and DP19.2) and in the north west at Pyramid Valley in Waikari (Fig. 5).

The Onepunga shell beds are thickest to the south east in Onepunga and are thinnest to the north west at Pyramid Valley (1.3m). Along Deans Range to the north east at DP19.1 the thickness measured was 2.5 and at DP19.2 it was also 2.5m thick.

C. Description

The Onepunga Shell Beds consist of shells that were both whole and broken, of bivalves and gastropods. The shells are tightly packed and appear to align with the bedding. The shells were surrounded and then infilled with well sorted, silty fine quartz sand. A large amount of shell material has been removed by dissolution and was replaced by sparry calcite.

Analysis found the carbonate content to range from c. 50 – 60%. There were a large proportion of whole shells present indicating that the faunal remains had not been transported any great distance. The quartz grains were subrounded and made up c. 30% of the composition. The detrital content in the Onepunga Shell Beds is considerably higher compared to the Whiterock Limestone.

Sandstone clasts from c. 10 – 20cm across occur toward the base of the Onepunga Shell Beds and were observed at sections along the Deans Range. McCulloch (1981) noted that the sandstone clasts got up to 30cm across.

On the Deans Range (DP19.1) the lower yellow – brown fine sandstone unit becomes laminated toward the top of the bed and the contact between the sandstone unit and the overlying Onepunga Shell Beds is undulatory. Here the mollusc casts are smaller compared to outcrops at Onepunga and Pyramid Valley. Sandstone clasts are also present in this section toward the base of the shell beds. The sandstone clasts are the same lithology as the yellow sandstones (section 2.3.1) indicating current activity ripped up the sandstone into the Onepunga Shell Beds during deposition.

D. Macrofossils

Although fossils are abundant, preservation is poor. Recognisable species included; *Serripecten hutchinsoni, Ostrea sp., Balanus sp.,* fish bone, scaphopods, including *Dentalium* and the gastropod *Polinices.*

2.3.4 North Dean Limestone

A. Distribution

The North Dean Limestone type locality is on the Deans Range at the highest point, North Dean (573m) and is interbedded with the Mount Brown Formation yellow-brown fine sandstones. The North Dean Limestone occurs as a narrow band extending from the northern extent of Mount Grey to the north east for 16km (Fig. 5). The interbedded yellow sands between the North Dean Limestone and underlying Onepunga Shell Beds also thicken to the north east.

At Onepunga road on the Mount Brown side there is an exposure of North Dean Limestone. Along the western slopes of Mount Brown the limestone exposures are minimal until the northern extent of Mount Brown where it is seen directly underlying Red Crag Limestone 2.

B. Thickness

The North Dean Limestone units that were measured ranged from 1.7m to 10m. Stratigraphic sections where the North Dean Limestone was measured include; Mount Brown 1 (3.4m), Mount Brown 3 (8m), Mount Brown 1.5 (1.7m), Mount Brown 5 (1.7m), and Mount Brown 2.6 (6.5m), Waipara River (2.5m), Dean Property 5.6 (10m), Dean Property 19.1 (5m) and Dean Property 19.2 (6m).

C. Description

The North Dean Limestone is a moderately to well indurated, yellow brown to reddish, poorly sorted, fine to coarse calcarenite; sandy quartz biosparite. The primary sedimentary structure that distinguishes the North Dean Limestone from the other limestones in the Mount Brown Formation is the presence of crossbedding (Fig.14).

The detrital content consisted of well sorted medium to coarse quartz grains that were subangular to subrounded. Included in the limestone were subrounded to rounded dark glauconite grains. Toward the base of the limestone are inclusions of yellow-brown sandstone clasts up to 30cm long, McCulloch (1981) found in some areas the clasts were up to 1m long.

The crossbedding in the North Dean Limestone suggests a change in depositional setting to a moderate to high energy environment compared to the Whiterock Limestone and the Onepunga Shell Beds. The size of the sandstone clasts indicate moderate to high current activity that ripped up the clasts from the sandstone. The North Dean Limestone has a higher detrital content compared to that of the Whiterock Limestone indicating a closed shelf occurring at a water depth down to 50m.

D. Macrofossils

The North Dean Limestone is the least fossiliferous of the Mount Brown Formation limestones examined. Many of the fossils present were highly fragmented The fragments of fossils that were recognisable included; branching bryozoa, echinoid spines, echinoid plates, coral fragments, bivalves (possibly *Serripecten sp.*), barnacle plates (*Balanus sp.*), brachiopods (possibly *Magadina waipariensis*), irregular echinoids and fish vertebra.

Irregular echinoids are often found in shifting sands from inner to mid shelf environments. The presence of fragmented branching bryozoa, corals and bivalves suggest a moderate to high energy environment where the fossil material was most likely transported and reworked from an inner shelf environment.

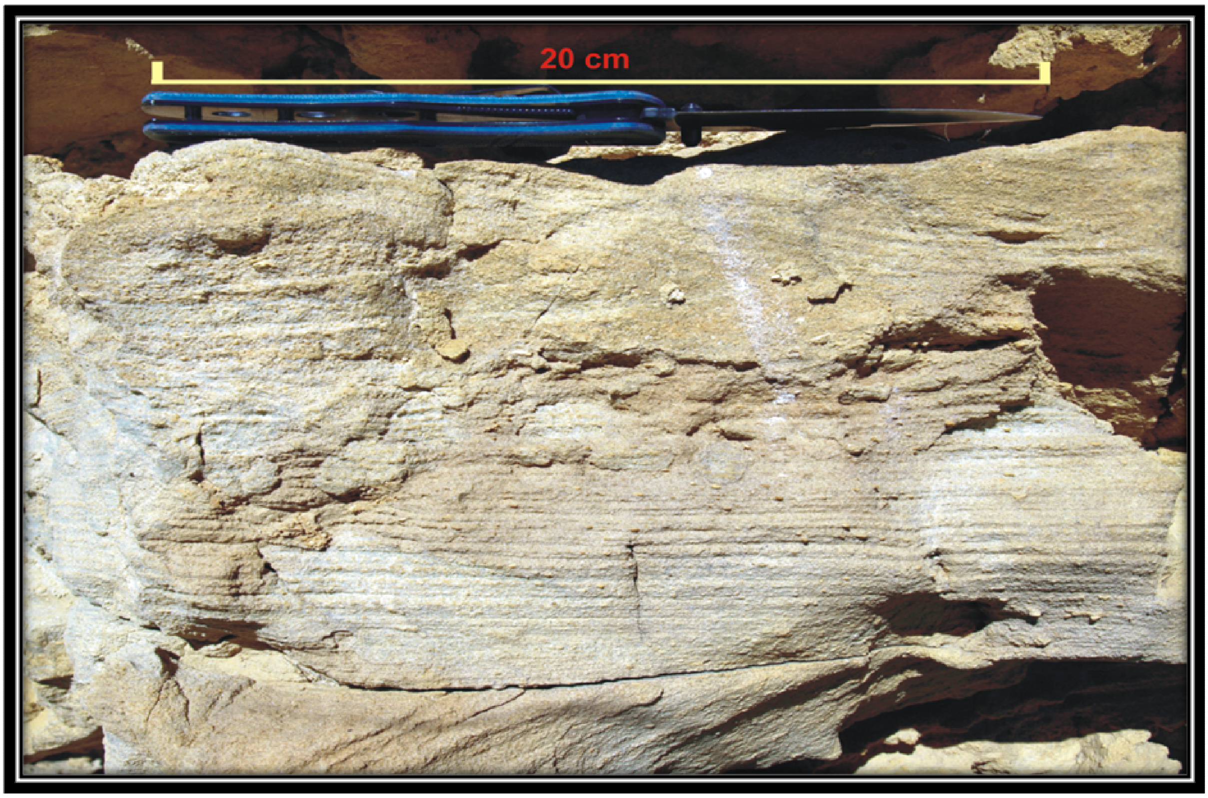


Figure 14. Crossbedding the characteristic feature of the North Dean Limestone.

2.3.5 Red Crag Limestone

A. Distribution

The distribution of the Red Crag Limestone is the most widespread and continuous compared to the other Mount Brown formation limestones that have been discussed in this chapter. The distribution of the Red Crag limestones does vary for Red Crag 1, 2 and 3. The Red Crag Limestones are separated by the yellow sandstones (Fig. 4).

The south western most extent of the Red Crag limestone's occur at Grey Fault where it extends along escarpments in Onepunga infrequently across to Mount Brown, in the Waipara River and along the Deans Range (Fig. 3 and 5). Earlier studies note the limestone's extend further to the north east up to Mount Donald (Thomson 1920; Wilson 1963; and McCulloch 1981). The Red Crag limestones were also recorded in the Kowai 1 Well sequence (Edwards et al 1979).

Red Crag limestone 1 is the oldest of the Red Crag limestone's and has the least continuous exposures and was not observed to the south east of Onepunga Road. To the north east of Onepunga Road the exposures of Red Crag Limestone 1 is inferred to intermittently outcrop along the western face of Mount Brown because it was unable to be clearly distinguished and appear more as thin outcrops. In the Waipara River, Red Crag Limestone 1 is not exposed between the North Dean Limestone and Red Crag Limestone 2. From North Dean the Red Crag

Limestone 1 is seen lying above the North Dean limestone and appears well below the Red Crag Limestone 2 and 3.

McCulloch (1981) suggested Red Crag 1 may represent single a depositional episode or are separate lensoidal deposits. Due to the intermittent nature of Red Crag 1 is not considered further in this chapter.

Red Crag limestone 2 is the most widespread and thickest out of all the limestones in the Mount Brown formation. The limestone can be clearly seen on the western side of Mount Brown (Fig.15). Red Crag 3 is predominantly seen overlying the Red Crag 2 limestone this is separated by a 1.5 – 2m band of yellow sandstone of the Mount Brown Formation (Fig.14A) it is traceable from Mount Brown to the north east into Weka Pass (Fig. 3).

The sandstone is yellow-brown, fine calcareous sand, moderately to well sorted, moderately indurated, massive sandstone. The sandstone is heavily bioturbated toward the top of the unit by *Ophiomorpha* (Fig.14B). The bioturbation ranges from moderate to heavy with the heavier bioturbation occurring progressively to the north east. The sandstone unit lying between the two beds contained fragmented fossil material of bryozoa and bivalves. The sandstone also has moderate to high levels of bioturbation that increase to the north east.

Figure 15. North eastern end of Mount Brown showing the Red Crag Limestones exposed on the western side.

B. Thickness

The Red Crag 1 limestone thicknesses ranged from 2 – 5m thick and were measured along the lower section of the Deans Range. Red Crag limestone was not identified in the sections on figure 2.

The thickness of the Red Crag 2 ranges from 10 – 33.5m. The Red Crag 2 was thickest on Mount Brown (25.5 – 31.6m). The Mount Brown 3 section (Fig.3) was only measured visually due to the remainder of the section being inaccessible. All the other sections on Mount Brown (MB1 and MB4 were measured without difficulty. Along the Deans range the thickness of Red Crag 2 ranged from 6.5 to 25m in thickness, the most common thickness was around 10m. The thickest section was at the south eastern end of the Deans Range. The thicknesses then stay at a relative constant between 6 to 10m to the north east. The thickness of Red Crag limestone 3 ranges between 2 to 7m thick. The thickest beds again occur on Mount Brown.

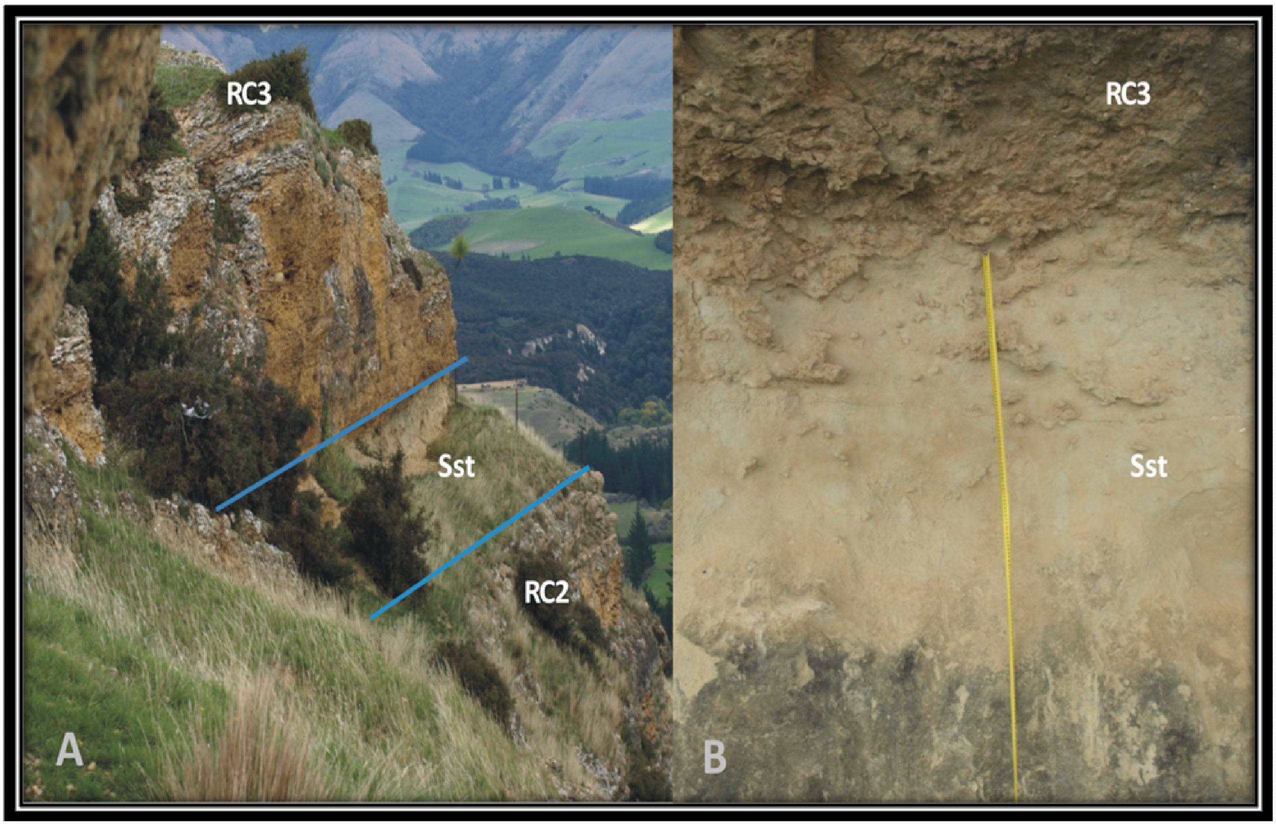


Figure 16. Photo A: Red Crag limestone 2 (RC2) and 3 (RC3) with sandstone layer (Sst) between the two limestone's, looking to the south. Photo B: Sandstone layer (Sst) layer showing an increase in bioturbation towards the top of unit. RC3 is the upper unit also indicating intense bioturbation in lower part of RC3.

C. Description

In outcrop both the Red Crag 2 and 3 limestones are rubbly in nature (Fig. 17A). The overall sedimentary composition of both Red Crag limestone 2 and 3 is nearly identical to the North Dean Limestone. The limestone is yellow-brown, fine to very coarse calcarenite, moderate to poorly sorted, moderate to very well indurated, massive; sandy quartz biosparite. The main compositional difference between the North Dean Limestone and the Red Crag Limestone is the faunal content, compared to the less fossiliferous North Dean Limestone. The Red Crag limestones also lacked the siltstone clasts that were seen near the base of the North Dean limestone.

Both Red Crag Limestone 2 and 3 were poorly sorted particularly toward the upper sections of the beds. The bioturbation levels in Red Crag Limestone 2 ranged from moderate to high and occurred all the way up the limestone. High levels of bioturbation occur at the contact between the yellow sandstones and Red Crag Limestone 3 which is seen in Figure 14B.

The composition of the limestones included; high levels of subangular to subrounded quartz grains. The glauconite content ranged from 1 – 6%. The grainsize of Red Crag Limestone 1 and 2 were predominantly fine to medium grained. Grain sizes in the Red Crag 3 typically ranged from medium to coarse.

D. Macrofossils

The Red Crag Limestone 1 contained highly fragmented fossil material that included; bryozoa, bivalves and some brachiopod fragments. Both the Red Crag 2 and 3 limestones contained a high number of fauna that were useful for palaeoenvironmental interpretations. There were six phyla represented; Brachiopoda, Mollusca, Bryozoa (Fig. 17B and C), Echinodermata, Foraminifera and Chordata. Corals were recorded in earlier work by McCulloch (1981) but in this study were not observed.

The most common occurring brachiopod in both Red Crag 2 and 3 were the species *Neobouchardia minima* and typically occurred in association with *Magadina* (Fig. 17D). The most common Terebratulid within the Red Crag 2 limestone is *Rhizothyris* which is associated with *Pachymagus.* Which has been described by previous workers as the *Rhizothyris – Pachymagus* Bed (Thomson 1920, Wilson 1963 and McCulloch 1981), this bed was seen in the upper sections of the limestone on Mount Brown, Waipara River and at the southern end of the Deans Range.

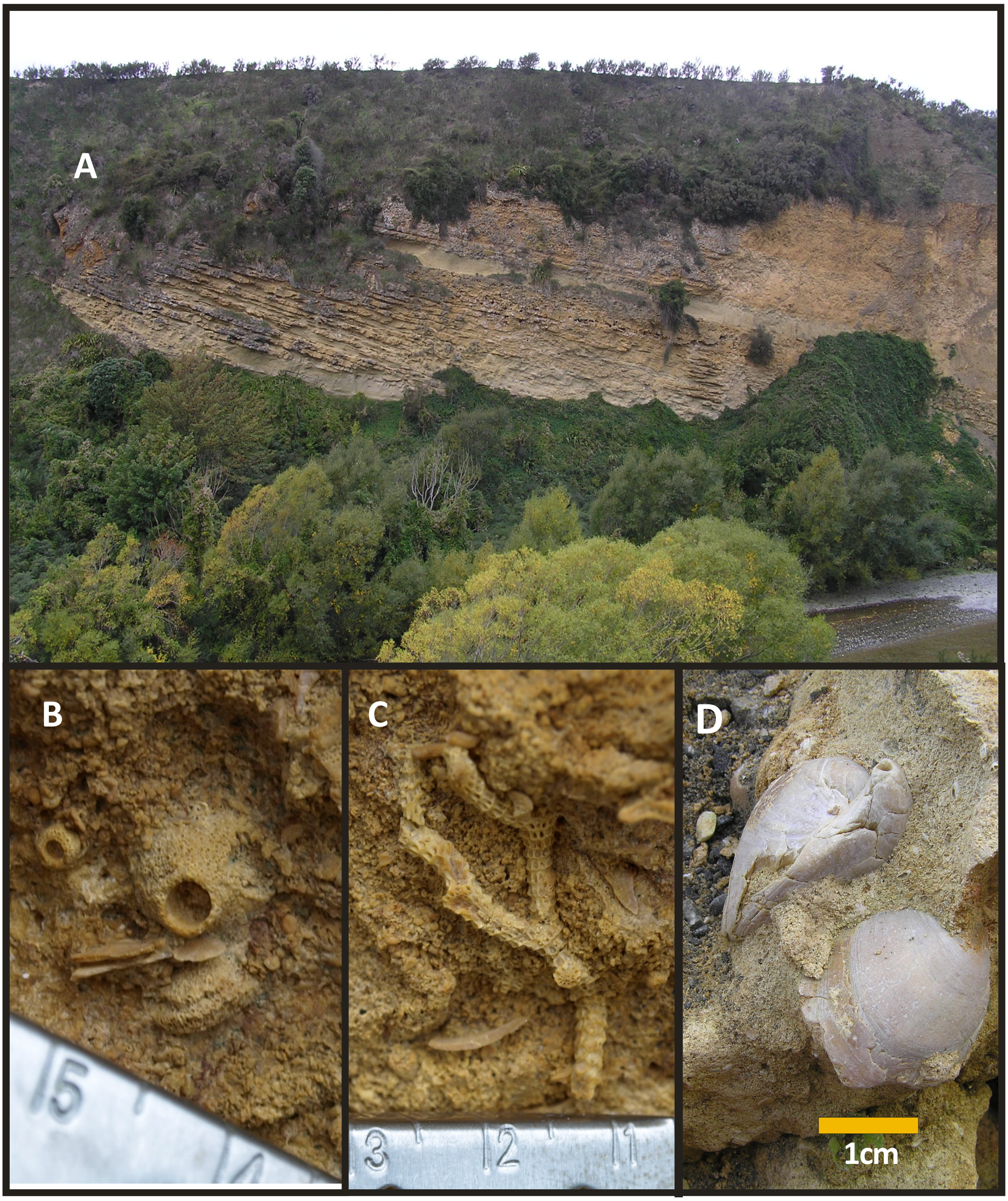


Figure 17. A. Outcrop characteristic of Red Crag Limestones, location on western side of Waipara River. B. Encrusting Bryozoa. C. Branching bryozoa in Red Crag Limestone 3. D. *Magadina* brachiopod in Red Crag Limestone 2. Scale is in centimeters for B – D.

The most common bivalve identified in both Red Crag Limestone 2 and was *Serripecten hutchinsoni*. Other bivalves that were commonly identified in Red Crag 2 and 3 included *Serripecten* n. sp., *Lentipecten* n. sp and *Ostrea.* The larger *Serripecten* n. sp were slightly more common in the Red Crag 3 limestone.

Bryozoans that were seen in the Red Crag limestones were often broken possibly due to transportation. The morphotypes that were identified included the fenestrate bryozoa, branching bryozoa and encrusting bryozoa. Branching bryozoa were the most common and often the least fragmented in places. The branching bryozoa were seen all the way through the Red Crag 2 limestone and more common than the fenestrate and encrusting bryozoa. The encrusting bryozoa were typically observed on brachiopod valves.

Chapter Three

Biostratigraphy of Waikari Formation and Mount Brown Formation

3.1 Introduction

Biostratigraphy focuses on the correlation and assignment of relative ages of rock strata by the use of fossil assemblages like foraminifera, as they have a widespread distribution, rapid evolution and are well preserved in substantial numbers (Hayward et al 1999). Foraminifera were used in this project as they were the most readily available for analysis. Foraminifera were identified and their relative ages were obtained from reference materials to determine the age range of the Waikari Formation and the Mount Brown Formation. The species of foraminifera identified from the Waikari Formation and Mount Brown Formation varied at each stratigraphic section.

The approach in this project for determining the relative age range of the Waikari Formation and the Mount Brown Formation was looking at first appearance datum (FAD) and last appearance datum (LAD) of foraminifera, and assessing each sample as an assemblage. Species that had longer age ranges but overlap the ranges of other taxa (concurrent-range zones) also provide a useful correlation to the age of the units when the FAD and LAD of the taxon identified overlap each other (Hornibrook et al. 1989).

In this study taxa that proved to be useful were ones of short stratigraphic age range which enabled constraints to be placed on the age of the Waikari and Mount Brown formations. Taxa were identified from quantitative sample picks of 242 – 306 individuals of foraminifera from selected stratigraphic samples. A secondary pick was attempted to identify more biostratigraphic significant taxa. There were some relatively long ranging taxa that were identified within the samples that were also able to assist in correlating the age of the units. Identification of foraminifera were primarily from Hornibrook (1961), Hornibrook et al. (1989) and Hayward et al. (1997).

Locations of the biostratigraphic columns, in Figure 18, include Onepunga farm, Mount Brown, Waipara River (middle branch), south branch Waipara River (Karetu Downs) and Pyramid Valley. Data from the Kowai 1 Well (Edwards et al. 1978) was also examined and used for correlating age ranges using foraminifera that were identified from the onshore shore well data. This chapter details individual sections and includes general data on planktic percentage that will be incorporated in chapter 4. The figures used in this chapter do not show all foraminifera identified; (All identified species in Appendix 3) species indicated in the figures were useful in determining the stratigraphic age range of the samples. Sample numbers in this thesis are keyed to original localities. These localities and samples are currently being entered into the Fossil Record File.

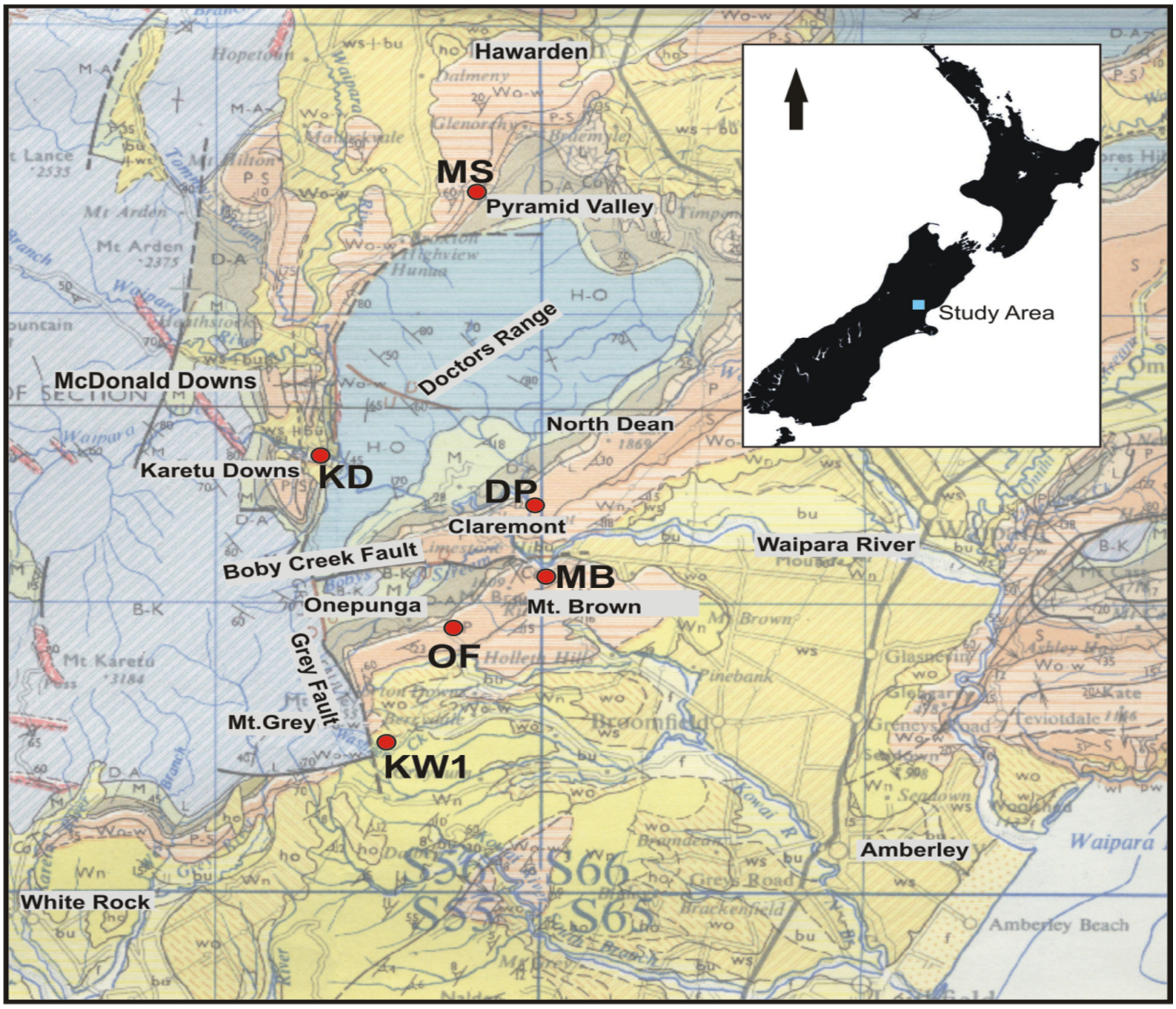


Figure 18. Study area in box indicated in blue. Locations of biostratigraphic columns indicated in red. KD = Karetu Downs, south branch Waipara River; MS = Moa Swamp, Pyramid Valley; DP = Dean Property, Waipara River; MB = Mount Brown 3; OF = Onepunga Farm; and KW1 = Kowai 1 Well. (Figure was modified from Sheet 18, Gregg et al. 1964)

The taxa examined in this study indicated that there were two key New Zealand stages to define; the Otaian and Altonian stage. This led to a brief review of stage name nomenclature for the Altonian stage, key New Zealand bioseries lineages and key biostratigraphic indicators in the Otaian and Altonian stages.

3.1.1 Stage Name Nomenclature

The Waikari and Mount Brown formations age assignments of previous mapsheets included the Awamoan, Hutchinsonian and Altonian stage. This study revises the age relationships of these units. Stage name nomenclature of the Altonian while identifying foraminifera required some clarification here. Before the Altonian was the common stage name in New Zealand, the Altonian was recognised as two separate stages, the Hutchinsonian and the Awamoan stages.

Finlay and Marwick (1947) included the Hutchinsonian and the Awamoan stages into the Pareora series, Southland; which is still in use today. It was Finlay and Marwick (1947) that proposed the Altonian stage, while retaining the Hutchinsonian and Awamoan. The definition of the Altonian stage interpreted by Finlay and Marwick (1947) was based on the first appearance of the fauna; *Planorbulinella zelandica* (primarily), *Cassidulina arata, Heterostegina, Cycloclypeus* and *Nephrolepidina* (Hornibrook 1989). A review of the biostratigraphy at Clifden, Southland; by Fleming et al (1969) better defined the Altonian stage.

Scott (1972) investigated Target Gully, Oamaru and found there was an overlap of the lower Altonian and the Hutchinsonian stage. This led to the suggestion by Scott (1972), that the Altonian required emending. The Awamoan and Hutchinsonian stages were unsuitable to be used and emended the stages all into the Altonian stage as part of the Pareora Series (Scott 1972). This was done by evaluating planktic foraminifera (primarily) that were suitable for the upper Otaian boundary and the lower Altonian stage boundary.

Morgans et al. (1999) discussed that the Otaian stage lowest limit was marked by *Ehrenbergina marwicki*, primarily. The *Haueslerella* lineage and *Plectofrondicularia* populations were identified as the lower boundary of the Altonian stage (Scott 1972).

3.1.2 Biostratigraphic Indicator Species

The usefulness of stratigraphic indicator species is dependent on accurate identification of the species (Bolli et al. 1985). Species of foraminifera were identified using a number of reference guides based on the foraminifera seen throughout New Zealand this included Hornibrook (1961), Hornibrook et al. (1989) and Hayward et al. (1997). Species identified were largely benthic foraminifera, as planktonic foraminifera observed were typically moderate to long ranging species in general and did not provide valuable constraints on the ages of the stratigraphic sections where foraminifera were sampled.

Hornibrook et al. (1989) summarised the main foraminiferal biostratigraphic basis for the 24 stages of the New Zealand Cenozoic with an emphasis of the faunas and their stratotypes. The distribution, sequential relations and characteristic foraminiferal assemblages were summarised. Notes on the fauna were selective with an emphasis on species that were relevant for correlation (Table 3.1).

Facies that typically characterise the Otaian stage represent mid to upper shelf facies like sandy siltstones and siltstones. The Otaian stage was primarily defined based on the FAD of *Ehrenbergina marwicki* (Hornibrook 1989). The species was identified from the middle of a strongly bedded basal part of Bluecliffs Siltstone, South Canterbury (1989).

Throughout most of New Zealand the Altonian stage has been correlated in a wide range of facies ranging from sublittoral, inner shelf to bathyal (Hornibrook et al. 1989). With the exception of the east coast of the South Island where it has been identified from warm subtropical water foraminifera (Hornibrook et al. 1989). Some of the key FAD species include *Cibicides thiaracuta* and *Textularia miozea* (Table 3.1) were observed in the samples from Waikari Formation and the Mount Brown beds.

3.1.3 New Zealand Bioseries Lineages

Foraminifera identified in the current study required a brief review of key New Zealand bioseries lineages based on some of the foraminifera identified. Hornibrook et al. (1989) discussed significant foraminiferal lineages that have been useful in correlating the Tertiary sequence of New Zealand which are noted bioseries. The bioseries are defined by the noticed changes in the things like; an increase in the number of chambers, changes from biserial to uniserial tests. Significant bioseries include; *Orbulina*, *Plectofrondicularia* and *Haeuslerella*. The Bolivinellidae, *Discorotalia, Elphidium* and *Notorotalia* genuses have also proven useful in determining biostratigraphic ages of New Zealand rock sequences.

The *Haeuslerella* group has a transition from elongate regularly biserial *Haeuslerella hectori* common in the Otaian, to *H. pukeuriensis* that has distinctly staggered terminal chambers and is one of the most useful criteria for locating the Otaian – Altonian boundary (Hornibrook 1989). *Textularia pseudomiozea* and *Plectofrondicularia proparri* are persistent through the Otaian stage. In the Altonian stage they are replaced by *T. miozea* and *P. parri.* However, these taxa are either absent or uncommon in samples from the Waikari and Mount Brown Formation.

Key Species Otaian Stage	FAD	LAD	Key Species Altonian Stage	FAD	LAD
Ehrenbergina marwicki	X		*Ehrenbergina marwicki*		X
Spiroloculina novozealandica	X		*Textularia miozea*	X	
Plectofrondicularia proparri	X		*Plectofrondicularia proparri*		X
Loxostomum pakaurangiense	X		*Cibicides thiaracuta*	X	
Planorbulinella zealandica	X		*Plectofrondicularia awamoana*		X
Anomailinoides fasciatus		X	*Bolivina zedirecta*	X	
Globorotalia minutissima	X		*Lenticulina calcar*	X	
Haeuslerella hectori		X	*Notorotalia spinosa*		X
Textularia pseudomiozea		X	*Globorotalia miozea miozea*	X	

Table 3.1 Table of key foraminifera species from the Otaian and Altonian stage based on the first appearance datum (FAD) and last appearance datum (LAD). Highlighted species were identified in study. Table modified from information provided by Hornibrook (1989).

The Bolivinellidae are not a common group; but are found in the Eocene to Miocene. There were two *Bolivinella* that are useful in constraining the age of the samples used in this study; *B. bensoni* (Waitakian to Altonian stage) and *B. australis* (Altonian stage). Notable species in the *Elphidium, Notorotalia* and *Cribrorotalia* lineages have also proven useful for determining biostratigraphy of strata. Species like Notorotalia serrata (Waitakian – Otaian to Altonian stage), *N. biconvexica* (Otaian to Southland Series) and *Discorotalia aranea* (Otaian to Altonian, mainly Altonian). These species were useful in constraining the age range of the samples that were collected in this study.

3.2 Waipara River Section

Six samples were taken for foraminiferal analysis to determine the biostratigraphic age range of the Waikari Formation and the Mount Brown Formation (Fig. 19). Samples included DP17.1A, DP10.4, DP14.2e, DP15.1A, DP3.5A and DP15.1e. The planktic foraminifera in the samples ranged from c.4 – 15%. The benthic foraminifera identified in the samples ranged from c. 85 – 95%. Agglutinated foraminifera were only identified in one of the six samples and only represented c. 1% of the total individual foraminifera identified.

Many of the taxa identified in the six samples were long ranging species that were not useful in constraining the age of either the Waikari and Mount Brown formations. The number of short age range species identified for each sample was 3 – 5 taxa (Fig. 19). These species were able to constrain the age range of each individual sample.

3.2.1 Sample DP17.1A

This sample was taken from the base of the Waikari Formation at 15.8m, in the Scargill Siltstone. The sample contained 4 species that had tight age constraints; *Ehrenbergina marwicki, Stilostomella finlayi, Nonionella zelandica* and *Anomalinoides fasciatus* seen in Figure 20.

Ehrenbergina marwicki (1 individual) is a distinct species with a first appearance datum occurring in the Otaian stage and last appearance datum occurs in the Altonian stage (Finlay 1939, in Hornibrook et al. 1989). *Stilostominella finlayi* (2 individuals) first appears in the Waitakian stage and has a last appearance datum in the Otaian stage (Hornibrook 1961). *Nonionella zelandica* (2 individuals) first appears in the Waitakian stage and last occurs in the Otaian stage (Cushman 1936, in Hornibrook 1961). *Anomalinoides fasciatus* (2 individuals) has a FAD in the Bortonian stage and LAD the Otaian stage (Hornibrook 1971 in Hornibrook et al. 1989).

A. Stratigraphic Age

The stratigraphic age of the sample indicated by the short age ranging species; *Nonionella zelandica, Bolivinella bensoni* (Fig. 17B), *Stilostominella finlayi* all have a last appearance datum in the Otaian stage. *Ehrenbergina marwicki* (Fig. 20) has a first appearance datum in the Otaian stage. Despite the relatively long age range of *Anomalinoides fasciatus* (Fig. 20) the last appearance datum of this species occurs in the Otaian stage. The first appearance and last appearance datum overlap confirming the sample has an Otaian age (Fig. 19).

3.2.2 Sample DP10.4

The sample was taken from the Gowan Hill Sandstone at 230.1m from the base of the section (Fig. 19). There were 29 taxa that were identified, from 298 individuals. Two species provided a constrained age range; *Bolivinella bensoni* (Fig. 20) and *Ehrenbergina marwick* (Fig. 20).

Bolivinella bensoni (8 ind.) has a FAD in the Waitakian stage and a LAD in the Otaian stage (Hayward 1982 in Hornibrook et al. 1989). The age range of *Ehrenbergina marwicki* was mentioned in the previous section and is seen in Figure 19.

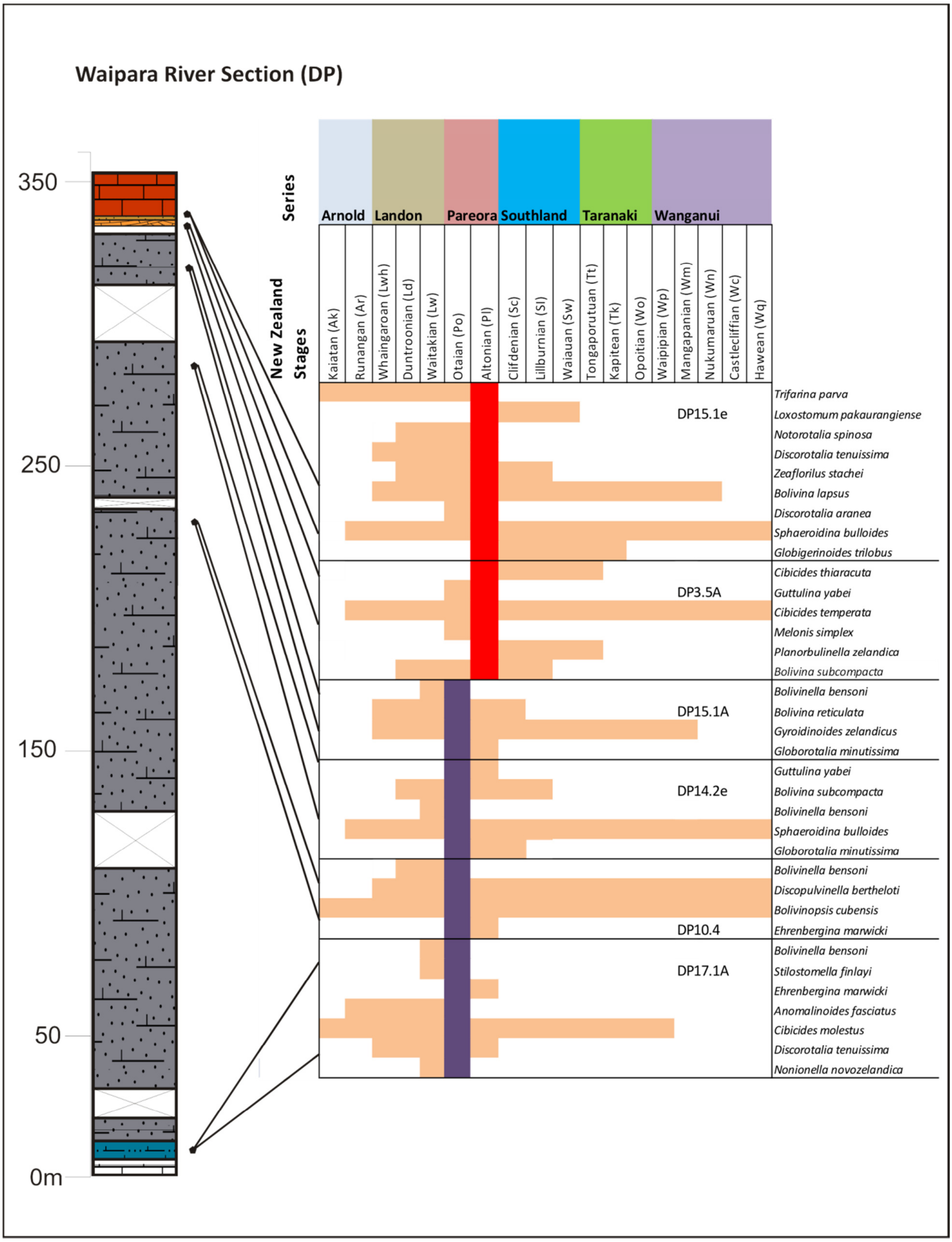


Figure 19: Biostratigraphy of Waipara River, Dean Property section. Light orange hashes indicate the stratigraphic range of foraminiferal species. Dark purple indicates Otaian stage age range. Red indicates Altonian stage age range. Not all New Zealand Stages and Series are included in diagram.

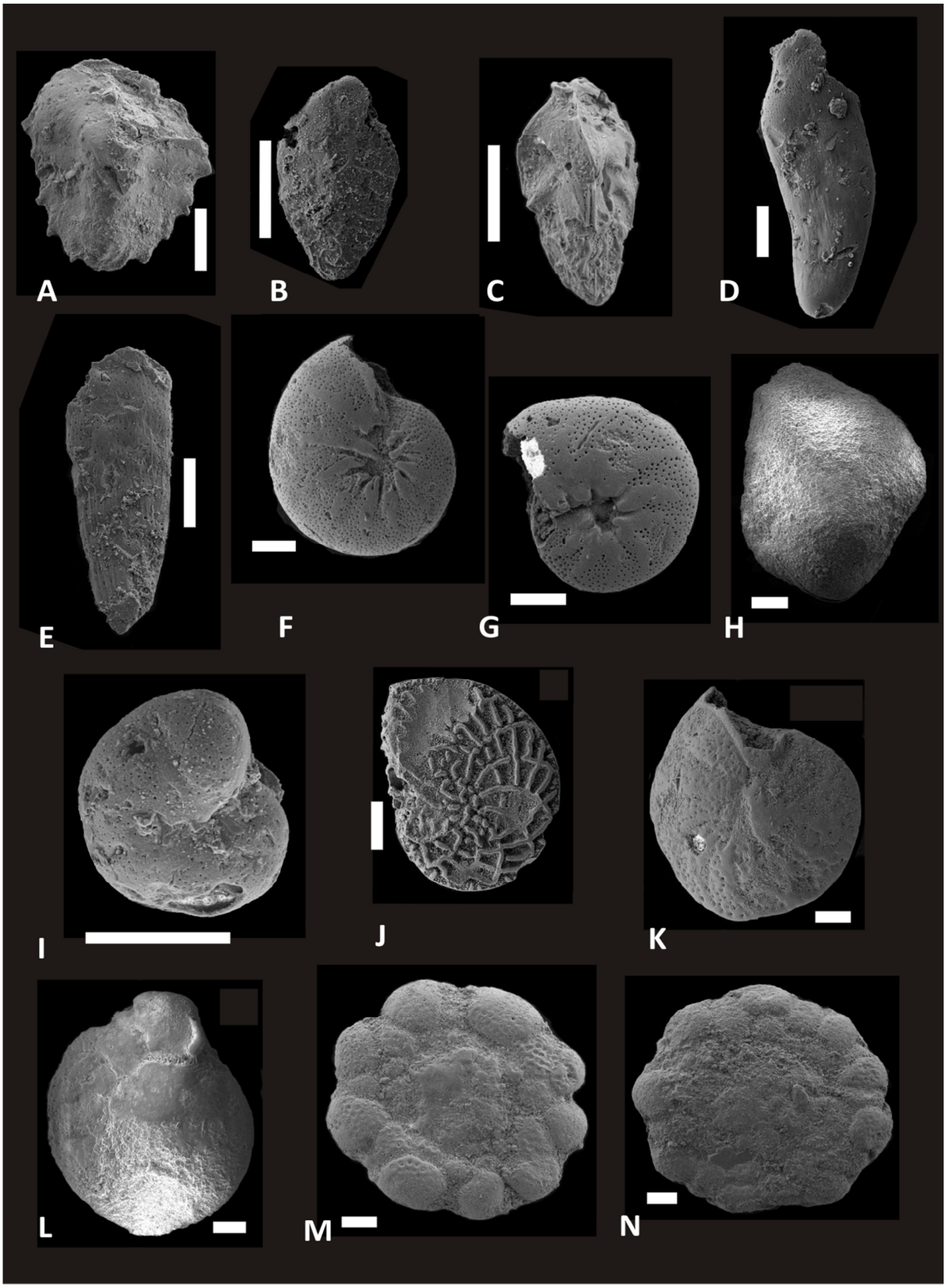


Figure 20. Key biostratigraphic species of foraminifera identified in samples. Scale Bars: 100µm. A: *Ehrenbergina marwicki*. B: *Bolivinella bensoni.* C: *Trifarina parva*. D: *Polymorphina waitakiensis.* E: *Bolivina zedirecta*. F, G: *Melonis simplex*. H: *Guttulina yabei*. I: *Anomalinoides fasciatus*. J: *Dicorotalia aranea.* K, L: *Cibicides thiaracuta.* M, N: *Planorbulinella zelandica.*

A. <u>Stratigraphic Age</u>

Based on the last appearance datum of *Bolivinella bensoni* in the Otaian stage correlates with *Ehrenbergina marwicki* last appearance datum occurs in the Otaian stage. This indicates that the age of the sample is Otaian as indicated in Figure 19.

3.2.3 Sample DP14.2e

This sample was taken from 280.1m up the stratigraphic column and within the Gowan Hill Sandstone (Fig. 19). The sample contained 35 taxa which were identified from 292 individuals. The sample contained 3 species that were able to provide detailed constraints on the age range from this sample.

The first was *Guttulina yabei* consisting of 1 individual (Fig. 20), has a FAD in the Otaian stage and LAD in the Altonian stage (Vella 1957 in Hornibrook et al. 1989). The second species identified for constraining the age of the sample was *Bolivinella bensoni* (4 ind.), this species age range was mentioned in the previous section (Fig. 19). The third species identified was *Globorotalia minutissima* (4 ind.) which has a FAD in the Otaian and LAD in the Clifdenian stage (Jenkins, 1957; in Hornibrook et al. 1989).

A. <u>Stratigraphic Age</u>

Guttulina yabei (Fig. 19) and *Globorotalia minutissima* both have a first appearance in the Otaian stage and overlap with the last appearance of *Bolivinella bensoni* (Fig. 19). Based on the first appearance and last appearance of these species overlapping confirms and age of Otaian, as seen in Figure 19.

3.2.4 Sample DP15.1A

The sample was taken from 320.5m up in the stratigraphic column from the Gowan Hill Sandstone. There were 33 taxa identified from a sample size of 297 individuals. Two taxa were identified for use with constraining stratigraphic age range include; *Bolivinella bensoni* and *Globorotalia minutissima* (Fig. 19). The stratigraphic age range of *Bolivinella bensoni* (4 ind.) and *Globorotalia minutissima* (4 ind.) have previously been discussed in earlier sections.

A. <u>Stratigraphic Age</u>

The first appearance datum of the species; *Loxostomum pakaurangiense* and *Globorotalia minutissima* in the Otaian stage correlate with the last appearance of the species *Bolivinella bensoni.* This correlates with an age of the Otaian stage (Fig.19).

3.2.5 Sample DP3.5A

Sample DP3.5A was taken from 333.1m in the stratigraphic column from the North Dean Limestone. 25 taxa were identified from an individual sample size of 300. The foraminifera that provided relatively constrained ages include *Planorbulinella zelandica* (Fig. 20), *Melonis simplex* (Fig. 20)*, Guttulina yabei* (Fig. 20) and *Cibicides thiaracuta* (Fig. 20) as seen in Figure 19.

Cibicides thiaracuta (28 ind.) has a FAD age in the Altonian and LAD in the Tongaporutuan stage (Hornibrook, 1958 in Hornibrook 1989). *Planorbulinella zelandica* (5 ind.) has a first FAD age in the Altonian and LAD in the Tongaporutuan stage (Finlay, 1947; in Hornibrook et al. 1989). *Melonis simplex* (3 ind.) has a FAD in the Otaian and LAD in the Altonian. *Guttulina yabei* (8 ind.) has a FAD in the Otaian and LAD occurs at the end of the Altonian (Vella, 1957; in Hornibrook 1961).

A. <u>Stratigraphic Age</u>

Cibicides thiaracuta and *Planorbulinella zelandica* have a first appearance datum of the Altonian stage. The last appearance datum of *Guttulina yabei* and *Melonis simplex* overlaps with the FAD of the two species mentioned, confirming an Altonian age (Fig.19)

3.2.6 Sample DP15.1e

Sample DP15.1e was taken from 335.8m up in the stratigraphic column from the Mount Brown yellow sandstone. There were 23 taxon identified from a sample size of 300 individuals. Six foraminifera useful in constraining the age range of the sample included *Loxostomum pakaurangiense, Trifarina parva* (Fig. 20), *Notorotalia spinosa, Discorotalia tenuissima, Discorotalia aranea* (Fig. 20) and *Globigerinoides trilobus* as seen in Figure 19.

Trifarina parva (1 ind.) has a FAD in the Bortonian and LAD in the Altonian (Hornibrook, 1961; in Hornibrook et al. 1989). *Loxostomum pakaurangiense* (1 ind.) has a FAD in the Altonian and LAD in the Waiauan (Hornibrook, 1958; in Hornibrook et al. 1989). *Notorotalia* *spinosa* (1 ind.) has a FAD in the Duntroonian stage and LAD in the Altonian stage (Hornibrook, 1966; in Hornibrook et al. 1989). *Discorotalia tenuissima* (2 ind.) has a FAD in the Whaingaroan stage and LAD in the Altonian stage (Hornibrook 1961, in Hornibrook et al. 1989). *Discorotalia aranea* (4 ind.) has a FAD in the Otaian stage and its LAD is in the Altonian stage (Hornibrook et al. 1989). *Globigerinoides trilobus* (6 ind.), FAD occurs in the Altonian stage and the LAD occurs in the Kapitean stage (Jenkins, 1971; in Hornibrook et al. 1989).

A. Stratigraphic Age

Many of the species have relatively long stratigraphic age ranges within this sample, though a number of species have a first appearance datum of the Altonian stage (*Loxostomum pakaurangiense, Discorotalia tenuissima, Notorotalia spinosa* and *Globigerinoides trilobus*). *Trifarina parva* and *Discorotalia aranea* have a LAD of Altonian stage. The overlapping FAD and LAD of the species correlate with an Altonian age (Fig. 19).

3.3 Mount Brown Section

The section on Mt Brown (Fig. 18) was used for biostratigraphic analysis was highly fossiliferous and rich in foraminifera. The benthic taxa were consistently more abundant than the planktic taxa, typically ranging between c. 83 and 93% of total foraminiferal fauna. The samples used for biostratigraphic analysis (Fig. 21) included MB3.1A, MB3.1F, MB3.1R, MB3.1H, MB3.1M and MB3.1P. The upper section measured was difficult to access so samples in this section were spaced close together (Fig. 21).

3.3.1 Sample MB3.1A

The sample was taken from the Scargill Siltstone 1.5m from the base of the section (Fig. 21). The sample contained a number of long ranging species that were unable to be used to refine the biostratigraphic age of the unit. There were 30 individual taxon identified from a sample size of 304 individuals and only 4 taxa in sample MB3.1A enabling correlation of the stratigraphic age of the unit.

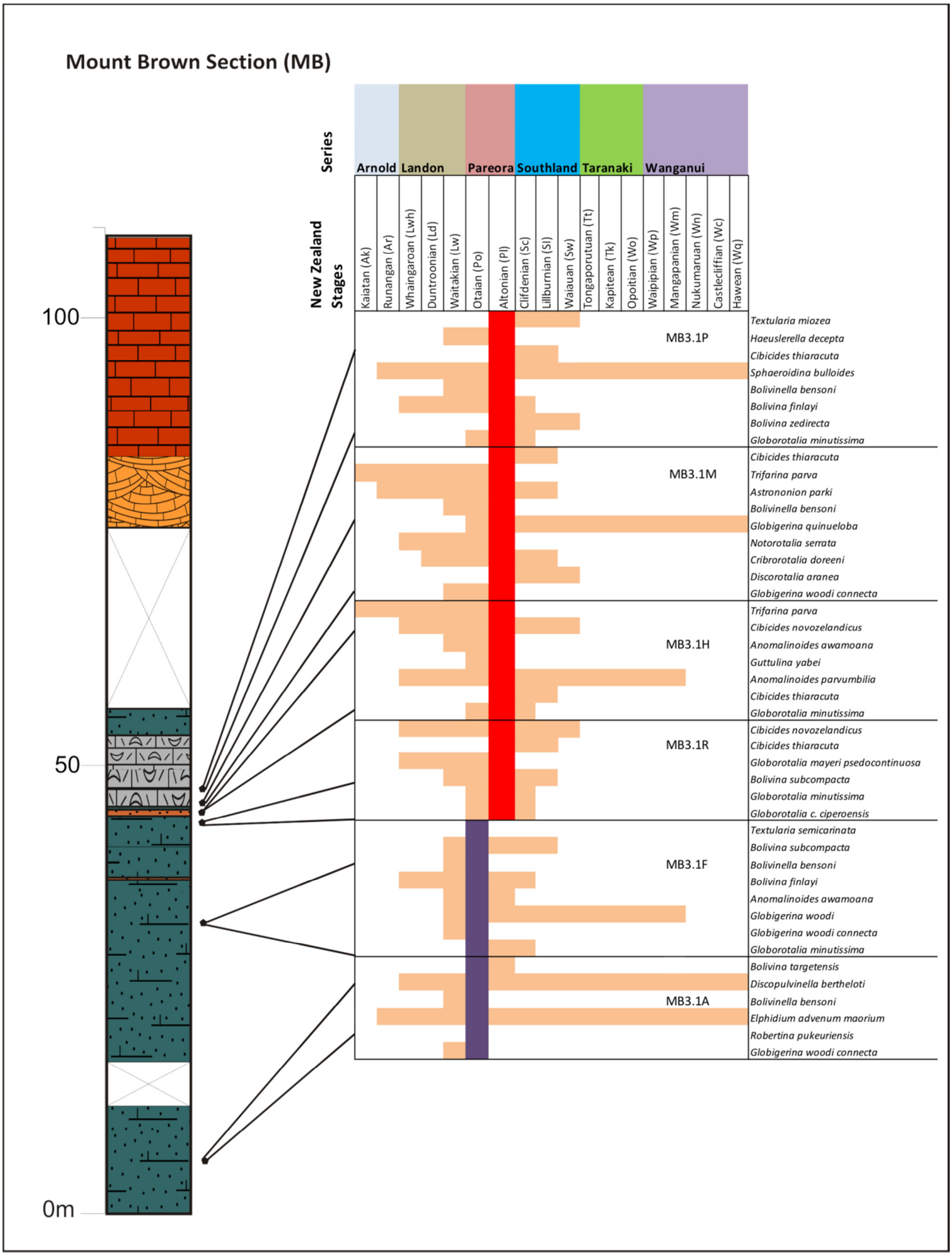


Figure 21. Biostratigraphy of Mount Brown. Light orange indicates the stratigraphic age range of foraminiferal species. Purple indicates Otaian stage age range. Red indicates Altonian stage age range. Not all of New Zealand Stages and Series are included in diagram.

The short ranging species include *Bolivina targetensis, Bolivinella bensoni* (Fig. 21)*, Robertina pukeuriensis* and *Globigerina woodi connecta*. The stratigraphic age range of *Bolivinella bensoni* (2 ind.) has been mentioned in previous sections of this chapter. *Robertina pukeuriensis* (1 ind.) is an even shorter ranging species with a

FAD and LAD in the Otaian stage (Hornibrook 1961). *Bolivina targetensis* (1 ind.) has a FAD in the Otaian and LAD in the Altonian stage (Hornibrook 1961). *Globigerina woodi connecta* (7 ind.) has a FAD of upper Waitakian to lower Altonian (Jenkins, 1964; in Hornibrook et al. 1989).

A. Stratigraphic Age

The species *Robertina pukeuriensis* has a well constrained age of Otaian and this is corroborated by the LAD of *Globigerina woodi connecta* and FAD of *Bolivina targetensis and Bolivinella bensoni*. This indicates that the sample is upper Otaian in age.

3.3.2 Sample MB3.1F

The sample was taken from the Scargill Siltstone from 33.5m from the base of the section. There were 31 taxa identified a sample size of 302 individual foraminifera. The sample contained c. 89% benthic and c. 11% planktic foraminifera. There were 4 samples that were short age ranging species that were useful in determining the age of this sample; *Textularia semicarinata*, *Bolivinella bensoni* (Fig.17) and *Globigerina woodi connecta*. The age ranges of *Bolivinella bensoni* (4 ind.) and *Globigerina woodi connecta* (20 ind.) have been mentioned in previous sections and can be seen in figure 3. The species *Textularia semicarinata* (1 ind.) has a FAD of Otaian stage and a LAD of Otaian stage (Hornibrook 1961).

A. Stratigraphic Age

Textularia semicarinata has a well constrained age in the Otaian stage. This species correlates with the last appearance datum of *Bolivinella bensoni* (Fig. 20) and *Globigerina woodi connecta.* This overlap confirms an age of Otaian (Fig. 21).

3.3.3 Sample MB3.1R

The sample was taken from 42.5m from the base of the section from the yellow sandstone (Fig. 21). 296 individual foraminifera were picked from the sample and 27 taxa were identified.

Only 2 taxa were identified from the sample that constrained the age range of sample MB3.1R; *Cibicides thiaracuta* (Fig. 20) and *Globorotalia mayeri pseudocontinuosa*.

Cibicides thiaracuta (4 ind.), FAD occurs in the Altonian stage and the LAD occurs in the Lillburnian stage. *Globorotalia mayeri pseudocontinuosa* (9 ind.) has a FAD in the Whaingaroan and LAD in the Altonian stage (Jenkins 1967, in Hornibrook et al. 1989).

A. Stratigraphic Age

The last appearance datum of *Globorotalia mayeri pseudocontinuosa* in the Altonian stage correlates with the first appearance datum of *Cibicides thiaracuta* (Fig. 21) confirming the sample as Altonian age (Fig. 21).

3.3.4 Sample MB3.1H

The sample was taken from 44.3m from the base of the section from the yellow sandstones of Mount Brown Formation (Fig. 21). There were 24 taxa identified from an individual sample size of 242. Again in this sample many of the foraminifera were long ranging species that will be more useful for palaeoenvironmental interpretation as seen in figure 4. Four species that were used in constraining the age of the unit, three had relatively short age ranges and one had a relatively long stratigraphic age range. The foraminifera included *Trifarina parva* (6 ind.), *Anomalinoides awamoana* (1 ind.), *Guttulina yabei* (1 ind.) and *Cibicides thiaracuta* (27 ind.) The age ranges of the species identified have been mentioned in previous sections and are seen in Figure 21.

A. Stratigraphic Age

The LAD of *Trifarina parva* (Fig. 21), *Anomalinoides awamoana* and *Guttulina yabei* (Fig. 21) occur in the Altonian stage. These species correlate with the FAD of *Cibicides thiaracuta* occurring in the Altonian stage. This correlation of these species indicates that the age of the unit is Altonian (Fig. 19).

3.3.5 Sample MB3.1M

The sample was taken from 47.7m from the base of the section the yellow sandstones of Mount Brown Formatio (Fig. 21) There were 28 taxa from 298 individuals were identified from the sample MB3.1M, in this sample 6 species were useful in constraining the age range of the sample these included; *Cibicides thiaracuta* (3 ind.), *Bolivinella bensoni* (2 ind.), *Trifarina parva*

(2 ind.) and *Discorotalia aranea* (1 ind.), *Globorotalia woodi connecta* (7 ind.) and *Notorotalia serrata* (2 ind.). The first 5 species have previously had their age ranges discussed in previous sections within the chapter and can also be seen in figure 3.

Notorotalia serrata has a FAD in the Waitakian and LAD in the Altonian stage (Finlay, 1939; in Hornibrook 1961). Hornibrook et al. (1989) noted that the species was particularly common. But based on the number of individuals identified would have occurred in the Altonian stage.

A. Stratigraphic Age

The first appearance datum of *Cibicides thiaracuta* (Fig. 20) and *Discorotalia aranea* (Fig. 20) occur in the Altonian and overlap with the last appearance datum's' of *Trifarina parva, Bolivinella bensoni* (Fig. 20), *Notorotalia serrata* and *Globigerina woodi connecta.* This correlation indicates an age of Altonian (Fig. 21).

3.3.6 Sample MB3.1P

The sample was taken from the Mount Brown limestone facies 49.5m from the base of the section (Fig. 21). There were 32 taxon identified from a sample size of 294 individuals. The sample contained a high percentage of benthic foraminifera (c.93%), a low amount of planktic foraminifera were observed (c.6%) and a very small amount of agglutinated foraminifera (c.1%).

There were 5 species that were used in determining the age of sample MB3.1P; *Textularia miozea, Haeuslerella decepta, Cibicides thiaracuta* (Fig. 20), *Bolivinella bensoni* (Fig. 20) and *Bolivina zedirecta*. The age range of *Cibicides thiaracuta* (40 ind.) has been mentioned in previous sections.

The agglutinated foraminifera, *Textularia miozea* (1 ind.) and *Haeuslerella decepta* (1 ind.) were useful two of the foraminifera that have short age ranges (Fig. 21). *Textularia miozea* has a FAD in the Altonian stage and is LAD in the Waiauan stage (Finlay, 1939; in Hornibrook et al. 1989). *Haeuslerella decepta* has a FAD in the Waitakian stage and LAD at the beginning of the Altonian stage (Hornibrook, 1961, in Hornibrook et al. 1989). *Bolivina zedirecta* (1 ind.) has a FAD in the Altonian stage and LAD in the Waiauan (Finlay, 1947; in Hornibrook et al. 1989).

A. Stratigraphic Age

The first appearance datum of *Textularia miozea, Cibicides thiaracuta* (Fig. 20) and *Bolivinella bensoni* (Fig. 20) of Altonian stage overlap with the last appearance datum of *Haeuslerella decepta* in the Altonian stage, which confirms the sample has an Altonian age (Fig. 21).

3.4 Onepunga Section

Three samples were taken from this stratigraphic column to determine stratigraphic age range (Fig. 18). The benthic foraminifera content in the samples ranged from c. 88 -90% and the planktic foraminifera ranged from c. 10 – 11.4%. The samples contained 29 – 31 taxa and contained 3 – 5 taxa of which were able to constrain the age of the samples. The samples used for biostratigraphic analysis included OF3.5A, OF3.4A and OF3.4D; see Figure 22 for sample locations.

3.4.1 Sample OF3.5A

The sample was taken 5m from the base of the section from the Gowan Hill Sandstone. There were 29 taxa identified from a sample size of 299 individuals. There were 4 taxa that were useful in constraining the age of the sample; *Bolivina pukeuriensis* (25 ind.), *Bolivinella bensoni* (2 ind.), *Plectofrondicularia proparri* (1 ind.), *Anomalinoides awamoana* (32 ind.) and *Globigerina woodi connecta* (14 ind.). The age ranges of *Bolivinella bensoni* and *Globigerina woodi connecta* previously been mentioned in earlier sections and can be seen in Figure 22. *Plectofrondicularia proparri* has a FAD in the Whaingaroan stage and LAD in the Otaian stage (Finlay, 1939; in Hornibrook et al. 1989).

A. Stratigraphic Age

The first appearance datum of *Bolivina pukeuriensis* in the Otaian stage overlaps with the last appearance datum of *Bolivinella bensoni* (Fig. 20), *Plectofrondicularia proparri* and *Globigerina woodi connecta* in the Otaian stage. These species correlate with an Otaian age (Fig. 22).

3.4.2 Sample OF3.4A

The sample was taken from 37m from the base of the section from the Gowan Hill Sandstone (Fig. 22). There were 30 taxa identified from a sample size of 298 individual foraminifera species. The sample had a high amount of benthic foraminifera (c. 88.6%) and low amount of planktic foraminifera (c. 11.4%) present in the sample. Six taxa were useful in constraining the age range of the sample include *Bulimina* n. sp. cf. *aculeata, Bolivinella bensoni, Polymorphina waitakiensis, Guttulina yabei, Discorotalia aranea* (Fig. 20) and *Globigerina woodi connecta* (Fig. 22).

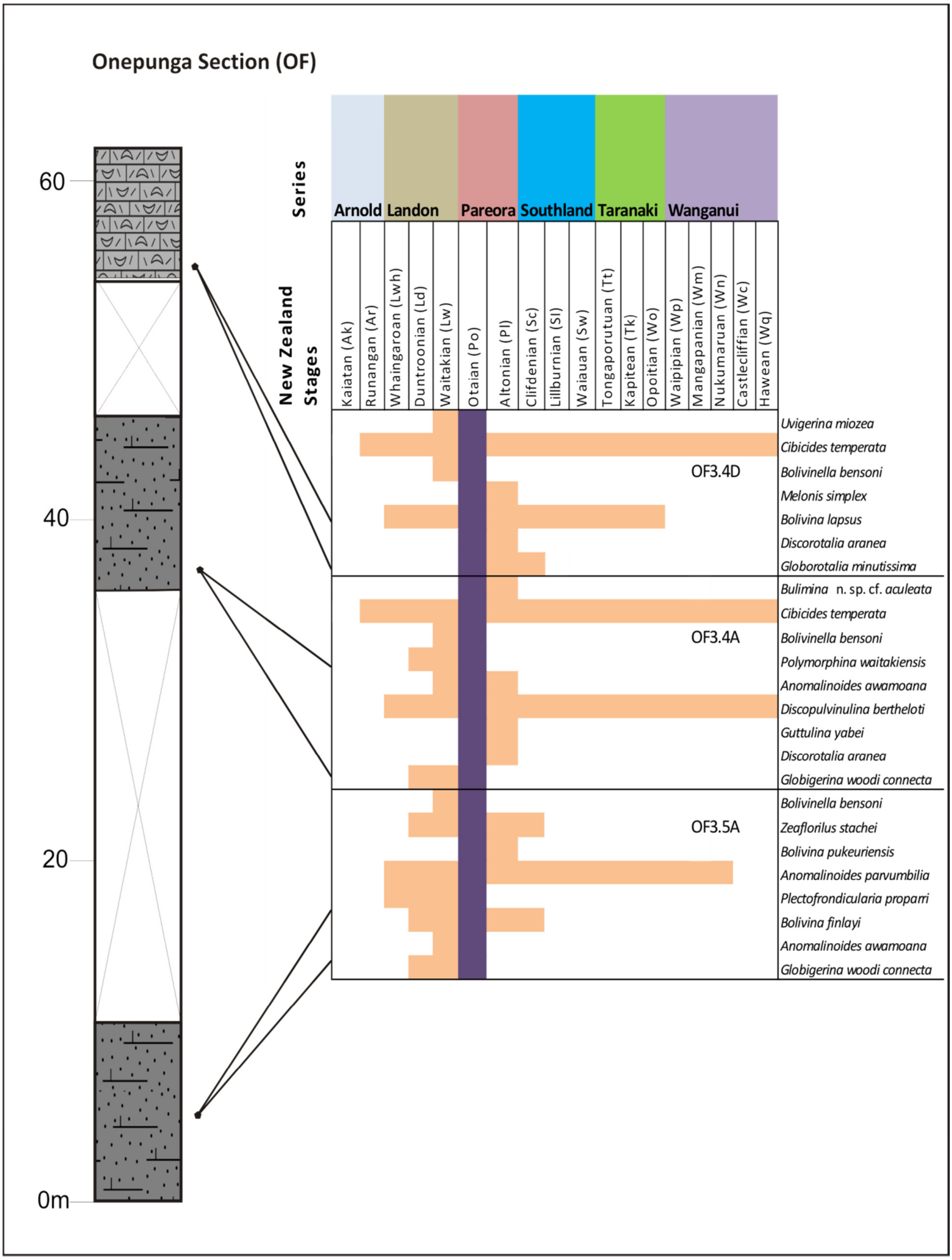


Figure 22. Biostratigraphy of Onepunga. Light orange indicates the stratigraphic age range of foraminiferal species. Purple indicates stage age range. Not all of the New Zealand Stages and Series are included in diagram.

Polymorphina waitakiensis (2 ind.) has a FAD the Duntroonian stage and LAD at the end of the Otaian stage (Hornibrook 1961). *Bulimina* n. sp. cf. *aculeata* (3 ind.) has a FAD in the Otaian stage and LAD in the Altonian stage (Hornibrook 1961). .

The 3 species; *Guttulina yabei* (1 ind.), *Discorotalia aranea* (1 ind.) and *Globigerina woodi connecta* (14 ind.) have already had the age ranges discussed in previous sections and can be seen in Figure 22.

A. Stratigraphic Age

The first appearance datum of *Anomalinoides awamoana, Guttulina yabei* (Fig. 17), *Bulimina* n. sp. cf. *aculeata* and *Discorotalia aranea* (Fig. 17) in the Otaian stage, correlate with the last appearance datum of *Globigerina woodi connecta, Polymorphina waitakiensis* and *Bolivinella bensoni* in the Otaian stage. This correlation indicates that the sample is Otaian in age (Fig. 20).

3.4.3 Sample OF3.4D

The sample was taken 55m from the base of the section from the Whiterock Limestone (Fig. 22). There were 30 foraminifera taxa identified from a sample size of 304 individuals. There were 5 species identified that had short stratigraphic age ranges; *Uvigerina miozea* (1 ind.), *Bolivinella bensoni* (5 ind.), *Melonis simplex* (1 ind.), *Discorotalia aranea* (3 ind.) and *Globorotalia minutissima* (7 ind.). The age range of these species have been previously been discussed in earlier sections, aside from *Melonis simplex* (Fig. 20) which has a FAD in the Otaian stage and a last appearance datum in the Altonian stage (Fig. 22).

A. Stratigraphic Age

The first appearance datum of *Melonis simplex* (Fig. 20), *Discorotalia aranea* (Fig. 20) and *Globorotalia minutissima* in the Otaian stage, correlate with the last appearance datum of *Uvigerina miozea* and *Bolivinella bensoni* in the Otaian stage, confirming that the sample is Otaian age (Fig. 22).

3.5 Karetu Downs Section

The Karetu Downs section is located in the middle branch of the Waipara River (Fig. 18). Five samples were taken from the base of the section to determine the stratigraphic age range (Fig. 23); KD2.2A, KD2.2f, KD2.2h, KD2.2m and KD2.2O. There were 25 – 33 taxa identified from sample a size of 267 – 303 individuals identified from the samples. There were 2 – 4 taxa that were useful in determining the stratigraphic age range in the samples. The benthic foraminifera from the samples ranged from c. 82 – 95% and the planktics from this section ranged from c. 5 – 18%.

3.5.1 Sample KD2.2A

The sample was taken 5m from base of the section from the Pahau Siltstone (Fig. 23). There were a total of 32 taxa identified from a sample size of 267 individual species. There were 3 foraminiferal species that were useful in determining the relative age of the sample. These included; *Bolivina pukeuriensis, Bolivinella bensoni* and *Globotorotalia minutissima.*

The age ranges of *Bolivinella bensoni* (2 ind.) and *Globorotalia minutissima* (4 ind.) have been discussed in previous sections and can be seen in Figure 23. *Bolivina pukeuriensis* (9 ind.) has a FAD in the Otaian stage and a LAD in the Clifdenian stage (Hornibrook 1961).

A. Stratigraphic Age

The first appearance datum of *Bolivina pukeuriensis* and *Globorotalia minutissima* in the Otaian stage overlap with the last appearance datum of *Bolivinella bensoni* (Fig. 20). This confirms a stratigraphic age of Otaian stage (Fig. 23).

3.5.2 Sample KD2.2f

This sample was taken 54m from the base of the section from the Scargill Siltstone (Fig. 23). There were 30 taxa identified from a sample size of 293 individuals. There were three taxa that were useful in determining the stratigraphic age range of the sample; *Bolivinella bensoni*, *Bolivina targetensis* and *Globorotalia minutissima.* The stratigraphic age range of the *Bolivinella bensoni* (4 ind.) and *Globorotalia minutissima* (3 ind.) have been mentioned in previous sections and can be seen in Figure 23. The FAD of *Bolivina targetensis* (1 ind.) occurs in the Otaian stage and a LAD in the Altonian stage (Hornibrook 1961).

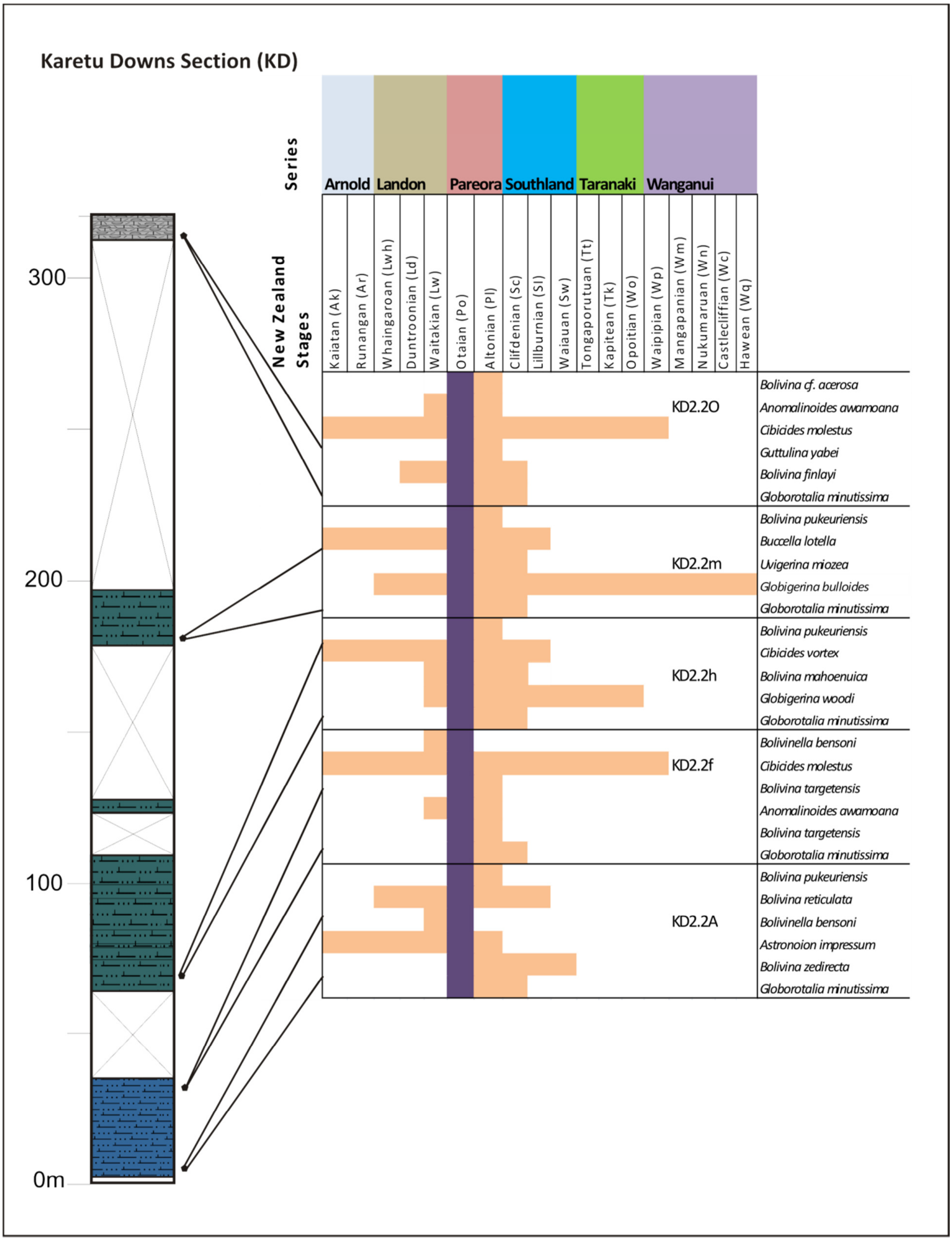


Figure 23. Biostratigraphy of Karetu Downs. Light orange indicates the stratigraphic age range of foraminiferal species. Purple indicates Otaian stage age range. Not all of the New Zealand Stages and Series are included in diagram.

A. Stratigraphic Age

The first appearance datum of *Bolivina targetensis* and *Globorotalia minutissima* overlap with the last appearance datum of *Bolivinella bensoni* (Fig. 20); this overlap of species confirms an age of Otaian stage (Fig. 23).

3.5.3 Sample KD2.2h

This sample was taken from the Scargill Siltstone in the stratigraphic section at 70m (Fig. 23). 34 taxa were identified from a sample size of 295 individuals. There were 2 species of foraminifera that had a relatively short stratigraphic age range; *Globorotalia minutissima* (10 ind.) and *Bolivina pukeuriensis* (23 ind.). The stratigraphic age range of these species was mentioned in previous sections and can be seen in Figure 23.

A. Stratigraphic Age

Both the first appearance datum of *Globorotalia minutissima* and *Bolivina pukeuriensis* occur in the Otaian stage, confirming an age of Otaian (Fig. 23).

3.5.4 Sample KD2.2m

The sample was taken from 172m from the base of the section from the Scargill Siltstone (Fig. 23). There were 25 taxa identified from a sample size of 303 individual foraminifera. Within the sample there were 3 taxa that were useful in determining the stratigraphic age range; *Bolivina pukeuriensis, Uvigerina miozea* and *Globorotalia minutissima* (Fig. 23).

The relative age ranges of *Globorotalia minutissima* (2 ind.) and *Bolivina pukeuriensis* (18 ind.) have been mentioned in previous sections and can be seen in Figure 23. The FAD of *Uvigerina miozea* (1 ind.) occurs in the upper Waitakian stage and the LAD occurs in the Otaian stage (Finlay, 1939; in Hornibrook 1989).

A. Stratigraphic Age

Globorotalia minutissima and *Bolivina pukeuriensis* have a FAD in the Otaian stage and overlap with the LAD of *Uvigerina miozea.* This confirms that the age of the sample is Otaian.

3.5.5 Sample KD2.2O

The sample was taken from 299m from the base of the section, from the Whiterock limestone (Fig. 23). From this sample 33 taxa were identified from a sample size of 268 individuals.

There were 3 species that had relatively short stratigraphic age ranges; *Bolivina cf. acerosa*, *Guttulina yabei* and *Globorotalia minutissima* (Fig. 23).

The age range of *Globorotalia minutissima* (3 ind.) and *Guttulina yabei* (Fig. 20) has been discussed in previous sections and is seen in Figure 23. *Bolivina cf. acerosa* (1 ind.) has a FAD in the Otaian stage and LAD in the Altonian stage (Hornibrook 1961).

A. Stratigraphic Age

The 3 species identified as useful for determining the stratigraphic age have FAD in the Otaian stage, confirms the sample has an age of Otaian (Fig. 23).

3.6 Pyramid Valley Section

There were 4 samples used to aid in determining the relative stratigraphic age range of the samples in Pyramid Valley (Fig. 24). The samples included MS2.1A, MS2.1E, MS2.1M and MS3.1E (Fig. 22). The samples consisted of 31 – 36 taxon from sample sizes of 296 – 306 individuals, with 4 – 10 taxon that were useful in constraining the relative ages of the units. The samples benthonic foraminifera ranged from c. 82.7 – 98% and the planktic foraminifera ranged from c. 2 – 17%.

3.6.1 Sample MS2.1A

This sample was taken at 2.4m from the base of the section, from the Scargill Sandstone (Fig. 24). There were 31 taxa were identified from 296 individuals sampled and had 4 species that had a relatively short stratigraphic age range that were useful in constraining the age range; *Bolivinella bensoni* (11 ind.), *Bolivina pukeuriensis* (5 ind.) and *Epistominella cassidulinoides* (3 ind.). The stratigraphic age ranges of the first 3 species of foraminifera have been mentioned in previous sections and are illustrated in Figure 24.

The age ranges of *Bolivinella bensoni* (11 ind.); *Bolivina pukeuriensis* (5 ind.) and *Globorotalia minutissima* (3 ind.) have been mentioned in previous sections and are seen in figure 6. *Epistominella cassidulinoides* has a FAD in the Otaian stage and LAD in the Clifdenian stage (Hornibrook 1961).

A. Stratigraphic AgeThe first appearance of *Globorotalia minutissima* and *Epistominella cassidulinoides* in the Otaian stage overlap with the last appearance of *Bolivinella bensoni* in the Otaian stage. This confirms that the age of the sample is Otaian (Fig. 24).

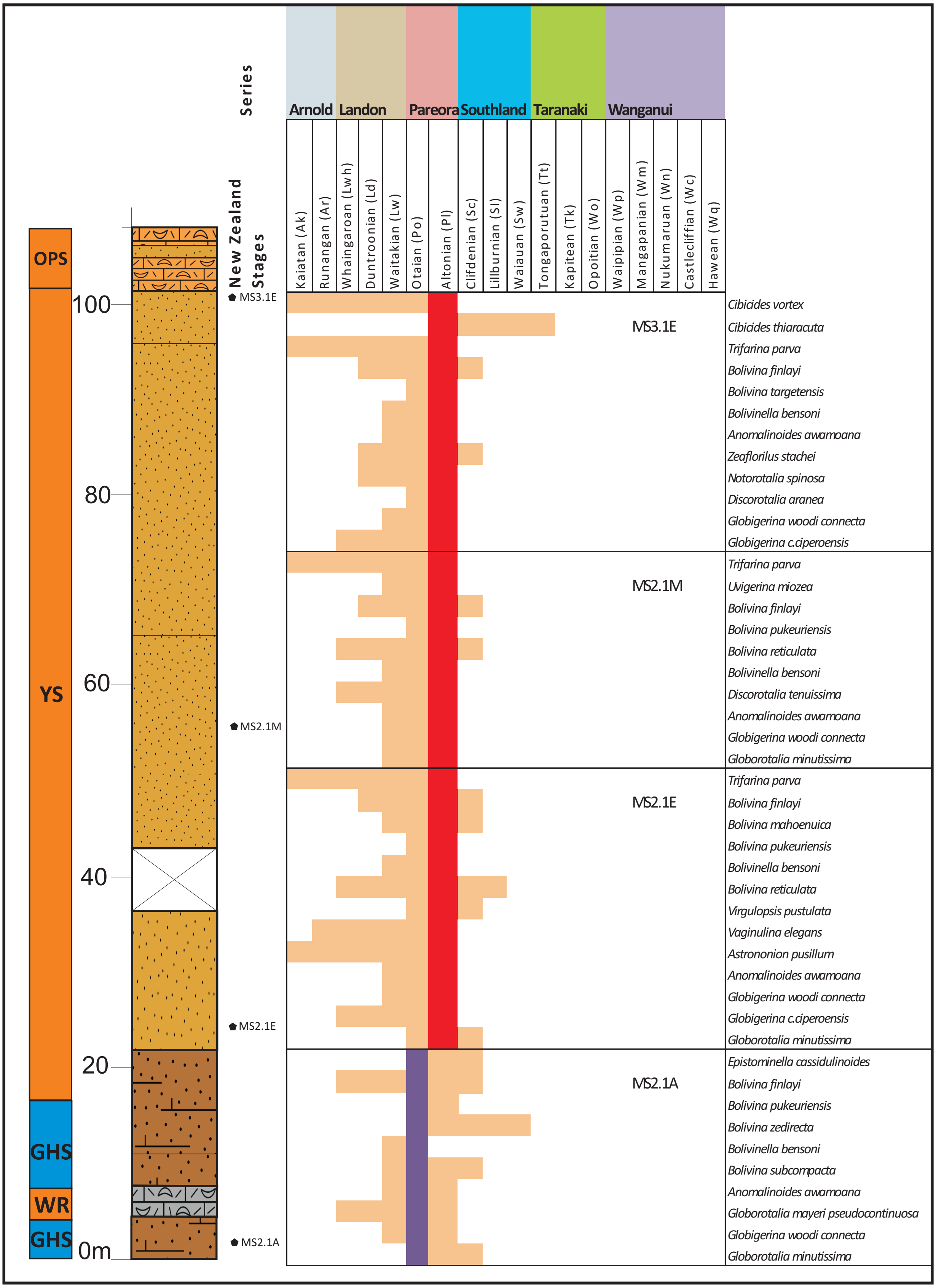


Figure 24. Biostratigraphy of Pyramid Valley. Light orange indicates the stratigraphic age range of foraminiferal species. Purple indicates Otaian stage age range. Not all of the New Zealand Stages and Series are included in diagram. PS: Pahau Siltstone. ScS: Scargill Siltstone. GHS: Gowan Hill Sandstone. WR: Whiterock Limestone. YS: Yellow Sandstone. ND: North Dean Limestone. RC: Red Crag Limestones

3.6.2 Sample MS2.1E

This sample was taken at 23.2m from the base of the section (Fig. 24) from the Mount Brown Formation yellow sandstones. There were 36 taxa identified from a sample size of 296 individuals. In the sample, 8 species were identified as being useful for determining the relative stratigraphic age range; *Anomalinoides awamoana, Astrononion pusillum, Bolivinella bensoni* (Fig. 20)*, Bolivina pukeuriensis, Trifarina parva* (Fig. 20)*, Vaginulina elegans* and *Globorotalia ciperoensis.*

The biostratigraphic age range of *Trifarina parva* (24 ind.)*, Bolivina pukeuriensis* and *Bolivina bensoni* (14 ind.) have been mentioned in previous sections and are seen in Figure 24.

The FAD of *Anomalinoides awamoana* (13 ind.) occurs in the Waitakian stage and LAD in the Altonian stage. *Vaginulina elegans* (1 ind.) has a FAD in the Runangan stage and LAD in the Altonian stage. The species *Astrononion pusillum* (7 ind.) has a FAD in the Kaiatan stage and LAD in the Altonian stage (Hornibrook 1961). *Globorotalia c. ciperoensis* (1 ind.) has a FAD in the Whaingaroan stage and LAD in the Altonian stage (Bolli, 1954; in Hornibrook 1989). The FAD of *Globigerina woodi connecta* (16 ind.) occurs in the upper Waitakian stage and LAD in the Altonian stage (Jenkins, 1964; in Hornibrook 1989).

A. Stratigraphic Age

The last appearance datum of *Trifarina parva, Bolivina pukeuriensis, Bolivinella bensoni, Vaginulina elegans, Astrononion pusillum, Globigerina woodi connecta* and *Anomalinoides awamoana* occurs in the Altonian stage (Fig. 24). This confirms an age of Altonian for sample MS2.1E.

3.6.3 Sample MS2.1M

The sample was taken at 56.2m from the base of the section (Fig. 24); yellow sandstone from the Mount Brown Formation. There were a total of 31 taxa identified from a total of 306 individuals. There were 7 species of foraminifera that were useful in constraining the age range; *Trifarina parva* (22 ind.)*, Bolivina pukeuriensis* (9 ind.)*, Uvigerina miozea* (2 ind.)*, Bolivinella bensoni* (7 ind.)*, Anomalinoides awamoana* (3 ind.)*, Discorotalia tenuissima* (2 ind.) and *Globigerina woodi connecta* (13 ind.). The stratigraphic age range of these species has been mentioned in previous sections and can be seen in Figure 22.

A. Stratigraphic Age

The last appearance of *Globigerina woodi connecta, Bolivinella bensoni* (Fig. 17)*, Uvigerina miozea* and *Bolivina pukeuriensis* and *Trifarina parva* in the Altonian stage (Fig. 22), confirms the sample age of Altonian.

3.6.4 Sample MS3.1E

This sample was taken at 94.8m from the base of the section (Fig. 24), from the yellow sandstones of the Mount Brown Formation. In the sample there were a total of 33 taxa identified from a sample size of 297 individuals. Nine foraminifera that had relatively short stratigraphic age ranges were recognised from the sample and used to constrain the age of the sample. The species included; *Cibicides thiaracuta* (Fig. 20)*, Trifarina parva* (Fig. 20) *, Bolivina targetensis, Bolivinella bensoni* (Fig. 20)*, Anomalinoides awamoana, Notorotalia spinosa, Discorotalia aranea* (Fig. 20)*, Globigerina woodi connecta* and *Globorotalia ciperoensis* (Fig. 24).

Bolivinella bensoni (2 ind.)*, Bolivina targetensis* (1 ind.)*, Anomalinoides awamoana* (17 ind.), *Trifarina parva* (3 ind.), *Discorotalia aranea* (7 ind.), *Globigerina woodi connecta* (3 ind.), *Notorotalia spinosa* (1 ind.), *Cibicides thiaracuta* (4 ind.), *Discorotalia aranea* (7 ind.) and *Globorotalia c. ciperoensis* (1 ind.) have had the stratigraphic age range discussed in previous sections and are seen in Figure 24.

A. Stratigraphic Age

The first appearance datum of *Cibicides thiaracuta* (Fig. 20) in the Altonian stage overlap with the LAD of *Trifarina parva* (Fig. 20)*, Bolivina targetensis, Bolivinella bensoni* (Fig. 20)*, Anomalinoides awamoana, Notorotalia spinosa, Discorotalia aranea* and *Globigerina c. ciperoensis.* This confirms and age of Altonian as seen in Figure 24.

3.7 Kowai – 1 Well Section

This data is drawn from Edwards et al. (1978) and is used to summarise the biostratigraphy and lithostratigraphy and biostratigraphy.

3.7.1 Mt Brown Formation (963 – 1070m)

The facies that the foraminifera were sampled from came from limestone, sandstone and siltstone facies. There were a number of foraminifera identified from the onshore well. The species with relatively short stratigraphic age ranges included; *Uvigerina miozea, Melonis* *simplex* and *Discorotalia aranea.* The stratigraphic age range of the unit was correlated to have a stratigraphic age range of Altonian stage. It was noted that the species *Discorotalia aranea* only rarely occurs in the Otaian stage and it is most common in the Waipara Region during the Altonian stage (Edwards et al. 1978).

3.7.2 Mt Brown Formation (1070 – 1083m)

The facies taken from this section of the core included sandstone and limestone. Species that was useful in correlating the stratigraphic age included *Haeuslerella hectori* (Waitakian to Otaian stage), *Textularia miozea* (Waitakian to Altonian), *Discorotalia aranea* (upper Otaian to Altonian), *Ehrenbergina marwicki* (Otaian to Altonian stage) and *Notorotalia "gagei"* (Waitakian to Altonian stage). These species observed indicated that the age of the facies of upper Otaian stage (Edwards et al. 1978).

3.7.3 Waikari Formation (1083 – 1223m)

The facies the foraminifera were identified from included siltstones, mudstones and glauconitic sandstones. The foraminifera that were useful in determining the age range of the Waikari Formation included; *Haeuslerella hectori* (Waitakian to Otaian stage), *Textularia semicarinata* (Otaian to Altonian stage), *Anomalinoides fasciatus* (Bortonian to Otaian stage) and *Ehrenbergina marwicki* (Otaian to Altonian stage). These species indicated an age range of Otaian stage (Edwards et al. 1978).

Chapter 4

Cluster Analysis and Detrended Correspondence Analysis

This chapter will present statistical analyses based on benthic foraminifera identified in the samples. This data can be found in Appendix 4. The goal was to perform cluster and multivariate analysis to identify common groups of foraminifera based on what the driving variables for distribution were.

4.1 Cluster Analysis

The primary aim of the cluster analysis in this part of the study was to aid in the palaeoenvironmental assessment of fossil foraminiferal faunas. This relies on the assumption that the fossil faunas are closely similar to modern faunas to aid in interpretation. Cluster analysis is a technique that attempts to find groupings on the basis of similarity and distinctiveness among species such as foraminifera (Valentine and Peddicord 1967). The technique looks to summarise sometimes large, complex data and place these objects into groups (Shi 1993; Hammer and Harper 2008).

The objective is to attempt to summarise similarities or dissimilarities among specimens. This classification of specimens allows for the determination and composition in each of the groups. So that a degree of association can be seen between two objects is at its maximum if they belong to the same group and minimal otherwise. It can also be used to discover structure in data providing neither an explanation nor an interpretation as to why the group exists.

There are potential problems involved such as the structure is superimposed and all specimens eventually cluster together. The multivariate data is compressed into a single dimension which can create a distortion in the representation of dissimilarities. Other problems can include determining the value of each group as the programme does not outline why they are grouped which can lead to a variation of interpretations.

It can be desirable to amend clusters or subclusters after their original formation this results in enlarged clusters that are no longer related but mutually exclusive (Valentine and Peddicord 1967). This can be done by removing species that are rare and using species that were frequently recorded in the samples.

The method used for cluster analysis was the Bray-Curtis model combined with two way modeling. "The method is used to determine site similarities based on organism abundances it reflects the differences between two samples due to both differing community composition and or differing total abundance" (Hammer and Harper 2006). .

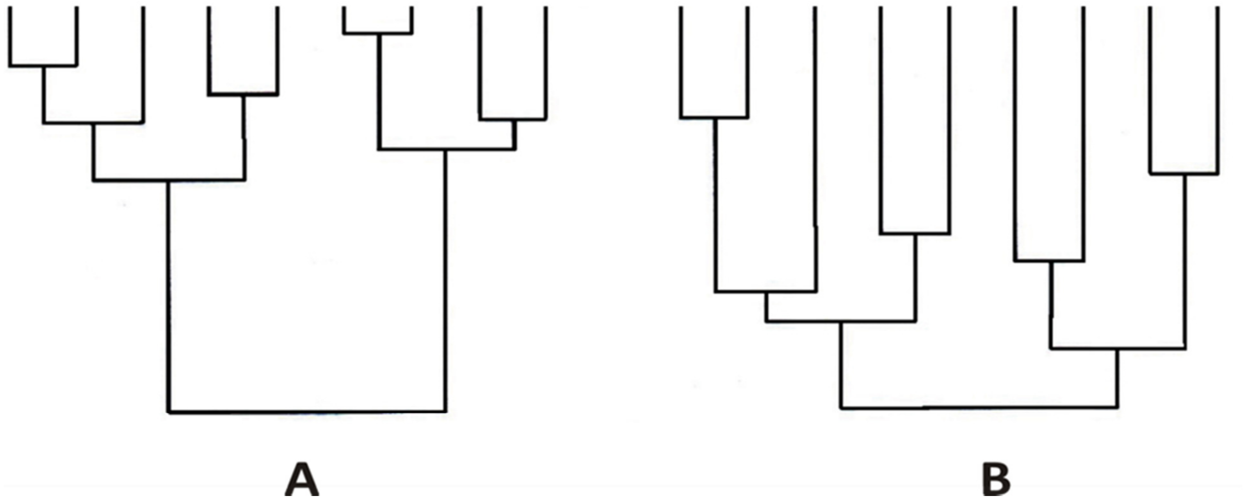


Figure 25. Two dendrograms with A showing well separated clusters and B not as well resolved. The clusters within B need to be interpreted with caution (image from Hammer 2002).

The Bray-Curtis method is sensitive to common taxa, data is produced in the form of a dendrogram as seen in Figure 25. The dendrogram shows the results linking similar specimens into groups. This dendrogram is constructed by finding a pair of specimens that share the smallest dissimilarities or the greatest similarities. Once the most similar pairs are found, the rest of the specimens are joined with existing clusters and those clusters are then joined together at several layers until all those clusters have been joined.

4.1.1 Examples of Previous Studies using Cluster Analysis and Detrended Correspondence Analysis

In this study cluster analysis and Detrended Correspondence Analysis (DCA) were used to assist in determining the palaeoenvironment of the Waikari and Mount Brown formations. Interpretations were based on modern analogues of foraminifera. A number of studies have been undertaken by other authors using cluster analysis to determine faunal associations of foraminifera to determine water depths. Examples in New Zealand include; Hayward and Brook (1994), Abbot (1997) and Hayward et al. (2003).

Recent studies of benthic foraminifera in the Taranaki Basin using cluster analysis (Hayward et al. 2003), found that using benthic foraminifera as an assessment for palaeo-depths can be reliable indicators when using recent benthic foraminifera as an analogue in studies.

In a similar study to this; Hayward and Brook (1994) used cluster analysis to determine the faunal associations and sample associations to aid in determining the palaeoecology and palaeoenvironments of Miocene rocks in the Waitemata Basin at Waiheke Island, New Zealand. Hayward and Brook (1994) used modern foraminiferal species as an analogue for interpreting the foraminifera during the early Miocene and determined a deepening of the basin due to subsidence based on changes in faunal and sample associations.

Abbott (1997) used cluster analysis for determining foraminiferal faunal associations to assist with determining the mid Pleistocene depositional sequences in the Wanganui Basin. The associations provided palaeo-bathymetry information and found that separate faunal associations were each related to both high stand systems tract and transgressive systems tracts (Abbott 1997).

4.1.2 Method

Samples were taken from stratigraphic sections to determine relative age range and to aid in the assessment of the palaeoenvironments by way of cluster analysis and detrended correspondence analysis (DCA). Samples were taken from Onepunga, Mount Brown, Waipara River, middle branch Waipara River (Karetu Downs) and Pyramid Valley. A total of 24 samples were used for cluster analysis, 240 - 305 individual foraminifera were picked from each sample.

A gridded sampling tray was numbered 1 – 45 using a random number generator, to select the order of grids to pick samples of foraminifera. This was to reduce bias during the sampling of foraminifera details are available from Random.org's website <http://www.random.org>. The foraminiferal families identified within each sample ranged from 11 – 18 and the number of species in the samples ranged from 24 – 38. The computer programme used for cluster analysis and detrended correspondence anlaysis in this study was PAST©, which is a data analysis package aimed at palaeontology (Hammer and Harper 2006).

Rarefaction was run through the PAST© programme to investigate the effect of sample size in taxon counts and compare taxon counts within samples of different sizes. Rarefaction allows the calculation of the species richness for a given number of sampled individuals and allows the construction of so called rarefaction curves. This curve is a plot of the number of species as a function of the number of individuals sampled. On the left, the steep slope indicates that a large fraction of the species diversity remains to be discovered. If the curve becomes flatter to the right, a reasonable number of individuals are sampled; even with more intensive sampling is likely to introduce only a few additional species.

In this study, the PAST© programme was used to run cluster analysis and detrended correspondence analysis to analyse foraminfera samples when:

- Planktics and rare species (< 1%) were removed
- All the species recorded in the samples. (Appendix 3)
- Rare species were removed. (Appendix 3)
- Rare species (< 5%) and planktic foraminifera were removed (see Appendix 2, Table 3)
- Foraminifera were grouped from species level to family level to determine similarities (Appendix 3)

The graph of the total number of individuals versus the number of taxa (Fig. 26) indicates that sampling up to 300 individuals is an accurate sampling size. There were two samples that had a low number of individuals (242 – 262). The number of taxa required indicating good diversity and representation of the samples is 24 - 30, which are within range of the smaller sampled foraminifera.

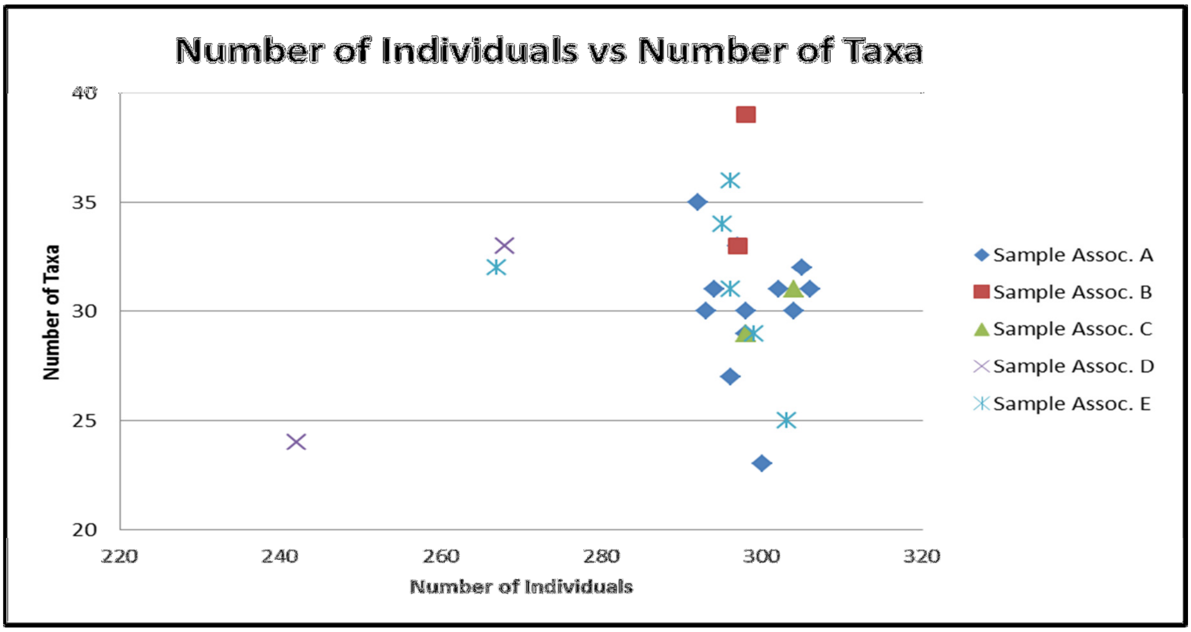


Figure 26. Individuals vs. Number of Taxa from Waipara – Waikari Samples.

In the analysis there were three measures of diversity were calculated for each foraminiferal faunal associations:

1. Fisher Alpha Index ($\alpha = N(1 - x)x$ (Hammer and Harper 2006), where N is the number of species in a sample and x is a constant related to the number of species (Hayward et al. 1999).

2. Evenness ($E = e^{H}/S$): S is number of species present. This is a measure of the evenness of species counts within a fauna irrespective of the number of species present (Buzas and Gibson 1969; Hill 1973). Faunal associations with the lowest evenness values have the greatest dominance of one species.

3. Shannon-Wiener Function ($H_{(S)} = \Sigma\, P_i \log_e P_1$): The value of H is dependent on a combination of the evenness of the species counts and with the number of species that are present (Hayward et al. 1999).

The evenness versus diversity graph of the sample associations was plotted to determine sample diversity and evenness (Fig. 27) and will be discussed in later sections of this chapter.

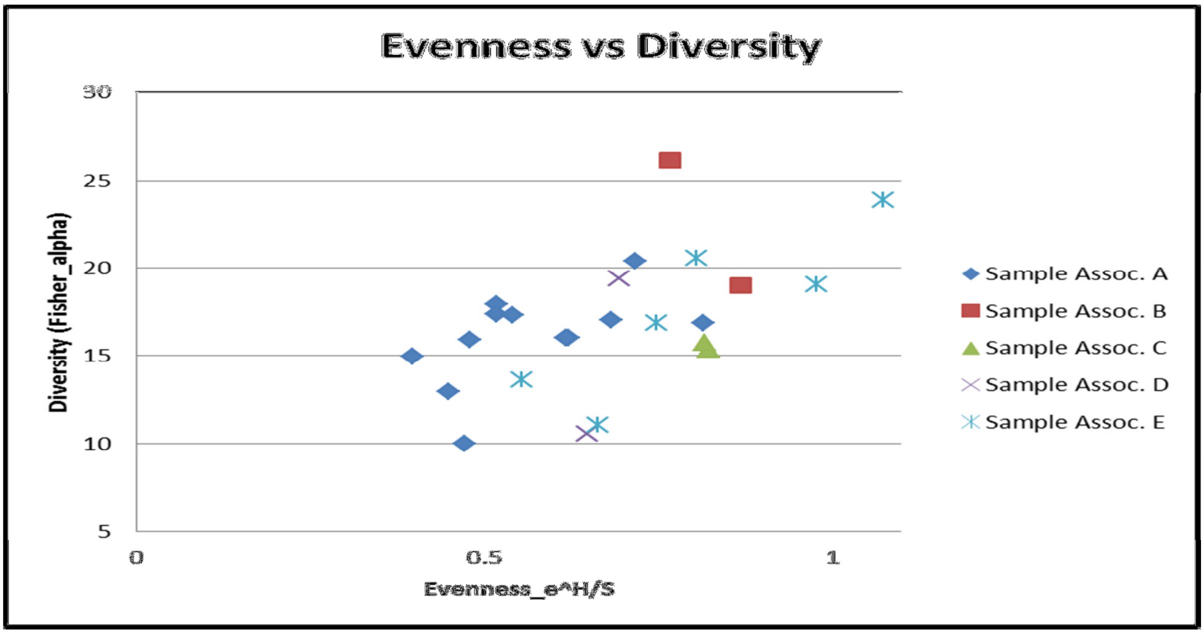


Figure 27. Evenness versus diversity plot of Sample Associations.

<u>4.1.3 Results: Cluster Analysis</u>

Results of the Bray – Curtis two way group cluster analysis are shown in Figure 27. Each Sample Association consists of one or more samples that are grouped together because of the of similarity component taxa. Cluster Analysis when removing rare and planktic species indicates that there are five main Sample Associations (Fig. 28):

- A: *Cibicides temperata/Cibicides perforatus*

- B: *Cibicides spp./Zeaflorilus stachei/Anomalinoides parvumbilia/Elphidium advenum maorium*

- C: *Cibicides spp./Globocassidulina* sp.
- D: *Elphidium* spp./*Cibicides* spp.
- E: *Bolivina finlayi/Globocassidulina* sp.

The Species Associations identified included (Fig.27):

1. *Lagena* Association
2. *Bolivina* Association
3. *Epistominella cassidulinoides/ Mississipina concentrica* Association
4. *Cibicides temperata/ Cibicides perforatus/ Cibicides* spp./ *Bolivina* spp. Association
5. *Zeaflorilus stachei – Virgulopsis costata* Asscociation
6. *Elphidium crispum crispum* Association
7. *Amphistegina* sp. Association
8. *Discorotalia aranea* Association
9. *Anomalinoides pinguiglabra* Association

10\. *Trifarina bradyi* Association

10\. *Nonionella* sp. Association

11\. *Polymorphina* sp. – *Bulimina* sp. Association

4.2 Sample Associations

4.2.1 Sample Association A: *Cibicides perforatus/ Cibicides temperata*

Sample association A consisted of 12 samples; MB3.1F (ScS), KD2.2f (ScS), OF3.4D (GHS), DP17.1A (ScS), OF3.4A (GHS), DP3.5A (ND), MB3.1R (YS), MB3.1M (YS), MB3.1P (RC), MS2.1M (YS), DP14.2e (GHS) and MS3.1E (YS). The grain size of the samples ranged from fine to coarse grained, as indicated in Figure 28.

Sample Association A, has a moderate to low diversity (Fig. 27). The evenness is low indicating that there is one dominant species within the samples. The samples are strongly associated with the species subassociation 4i, where the dominant species in this cluster is *Cibicides temperata* followed by *Cibicides perforatus*. *Cibicides temperata* and *C. perforatus* are abundant in all the samples from fine to coarse grained.

Cibicides temperata ranged in relative abundance from c. 5.5 – 38.9% (Fig. 27) and *Cibicides perforatus* relative abundances ranged from c. 7 – 33.3% (Fig. 27) within all the samples. *Globocassidulina* sp. (c. 4.3 – 11%) is also present in 11 out of the 12 samples, making up a moderate constituent of the Sample Association. Key species from Sample Association A are seen in Figure 29.

The other species included in the Sample Association are seen in Figure 28. Overall *Cibicides perforatus* (Fig. 29) and *Cibicides temperata* (Fig. 29) are the dominant species in Sample Association A. Other species including *C. novozelandicus* (c. 1.5 – 18%), *C. thiaracuta* (c. 1.1 – 16%) make up the second largest constituent in the faunal association. Cibicides thiaracuta has a first appearance datum in the Altonian stage (Hornibrook 1958 in Hornibrook 1989) and is restricted to the samples of this age. The grain size of the samples that contained *C. thiaracuta* was medium to coarse grained.

<u>Palaeoenvironmental Indicators</u>

The genus *Cibicides* are an epifaunal group where the life mode is attachment to substrates such as rock or shell material (Murray 2006). This mode of life for *Cibicides* requires environments with rock or shell material and *Cibicides* are typically found at water depths that range from 50 – 200m (Hayward 2003).

The genus *Anomalinoides* is typically found from inner – mid shelf water depths (Hayward 2004). The species *Melonis simplex* (Fig. 20F,G) was only identified in sample DP3.5A and represents less than 5% of the relative abundance. It has been identified in water depths that range from inner – mid shelf depths (Hayward 2004). *Elphidium crispum crispum* and *Cibicides thiaracuta* form a minor constituent in the Sample Association. These species are typically found at inner shelf depths when they have a higher relative abundance, if they have a lower relative abundance, as is the case in this association they may have been transported down the shelf slope after death (Hayward 2004). Sample Association A indicates a water depth range of outer inner shelf to mid shelf, predominantly mid shelf water depths benthic foraminifera.

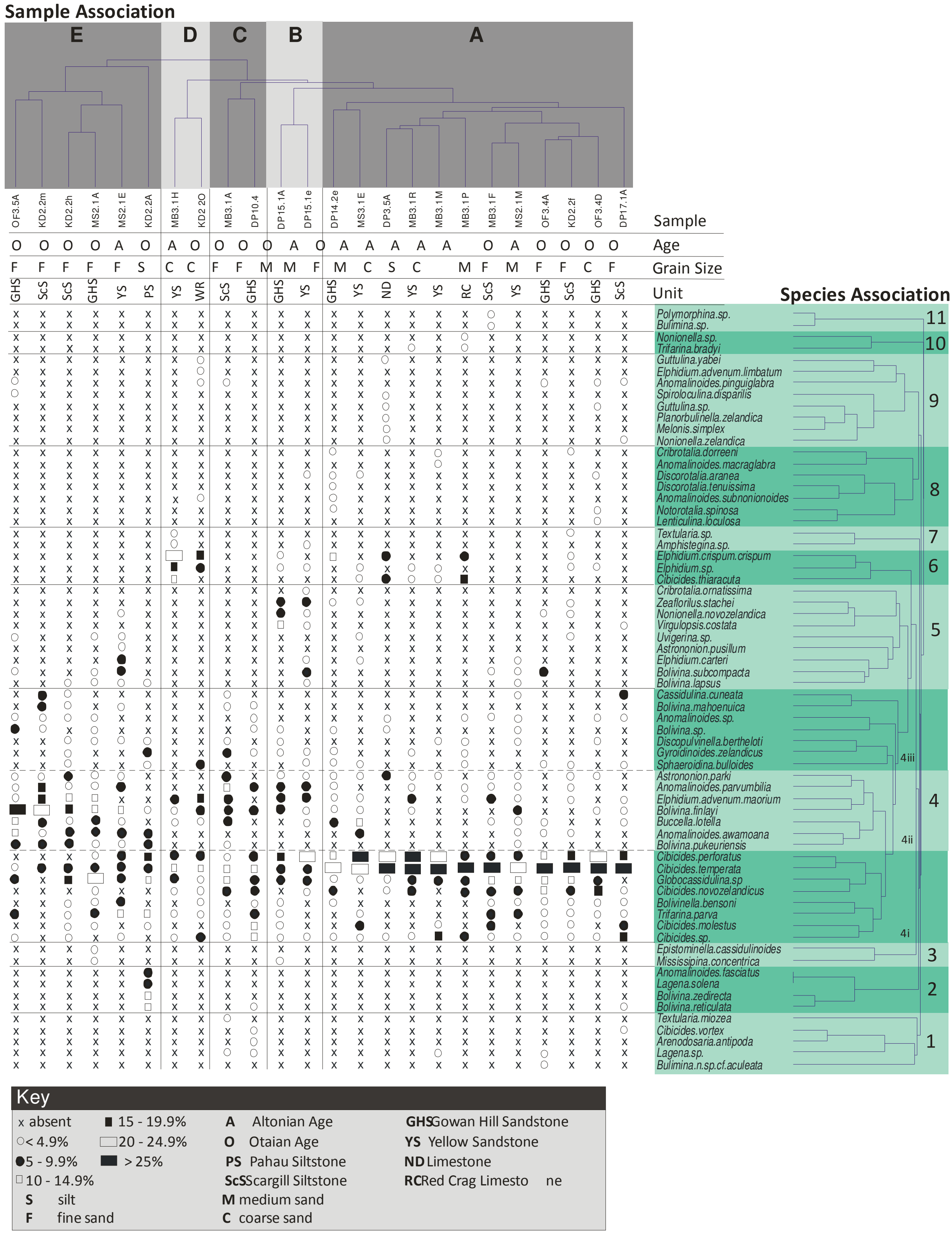


Figure 28. Bray-Curtis two way analysis with Sample Associations (A – E) and Species Associations (1 – 11). Dashed lines indicate species subassociation 4i –iii.

4.2.2 Sample Association B: *Cibicides spp./ Zeaflorilus stachei/ Anomalinoides parvumbilia/Elphidium advenum maorium*

The cluster analysis correlated only two samples; DP15.1A and DP15.1e within this Sample Association. Sample DP15.1A is from the Gowan Hill Sandstone and is a medium sandstone. Sample DP15.1e came from the bioturbated yellow sandstone between the North Dean Limestone and the Red Crag Limestone 2. Sample Association B (Fig. 27) has a high evenness indicating a high diversity of species.

Foraminifera that represent Sample Association include: *Cibicides perforatus, C. temperata, Zeaflorilus stachei* and *Globocassidulina* sp, *Anomalinoides parvumbilia, Elphidium advenum maorium* and *Virgulopsis costata*. The dominant species in Sample Association B is *Cibicides perforatus* (Fig.28). In sample DP15.1A the relative abundance of the species is c. 20%, in sample DP15.1e it is c. 16.4% (Fig. 28).

Other species of the genus *Cibicides* were present but only as a minor constituent. *Zeaflorilus stachei* was represented in both samples (Fig. 28). The relative abundance in sample DP15.1A of *Zeaflorilus stachei* (Fig. 29) was c. 7.4% and in DP15.1e c. 6.8%. *Globocassidulina* sp. (Fig. 29) is seen in both the samples and the relative abundances range from 5 – 10% within the faunal association (Fig. 28). *Anomalinoides parvumbilia* (Fig. 28) relative abundance in sample DP15.1A was c. 5% and in sample DP15.1e was c. 5.3%. The genus *Nonionella* is also present as a minor constituent. The relative abundance of *Virgulopsis costata* in sample DP15.1A is c. 11.7% and in DP15.1e is c. 3.8%. The relative abundance of *Elphidium advenum maorium* was c. 5.1% (DP15.1A) and c. 10.1% (DP15.1e).

Palaeoenvironmental Indicators

Cibicides perforatus forms a large constituent of this association. This species is typically found at mid shelf water depths (Hayward 2003). *Elphidium advenum maorium* occur in mid to outer shelf water depths, typically when associated with *Nonionella* and *Cibicides* (Hayward et al. 1997). The genus *Virgulopsis* is typically found in inner to mid-shelf water depths (Hayward and Brook 1994). The fine sandstone facies seen in the faunal association and the water depths associated with the fauna suggest mid shelf water depths.

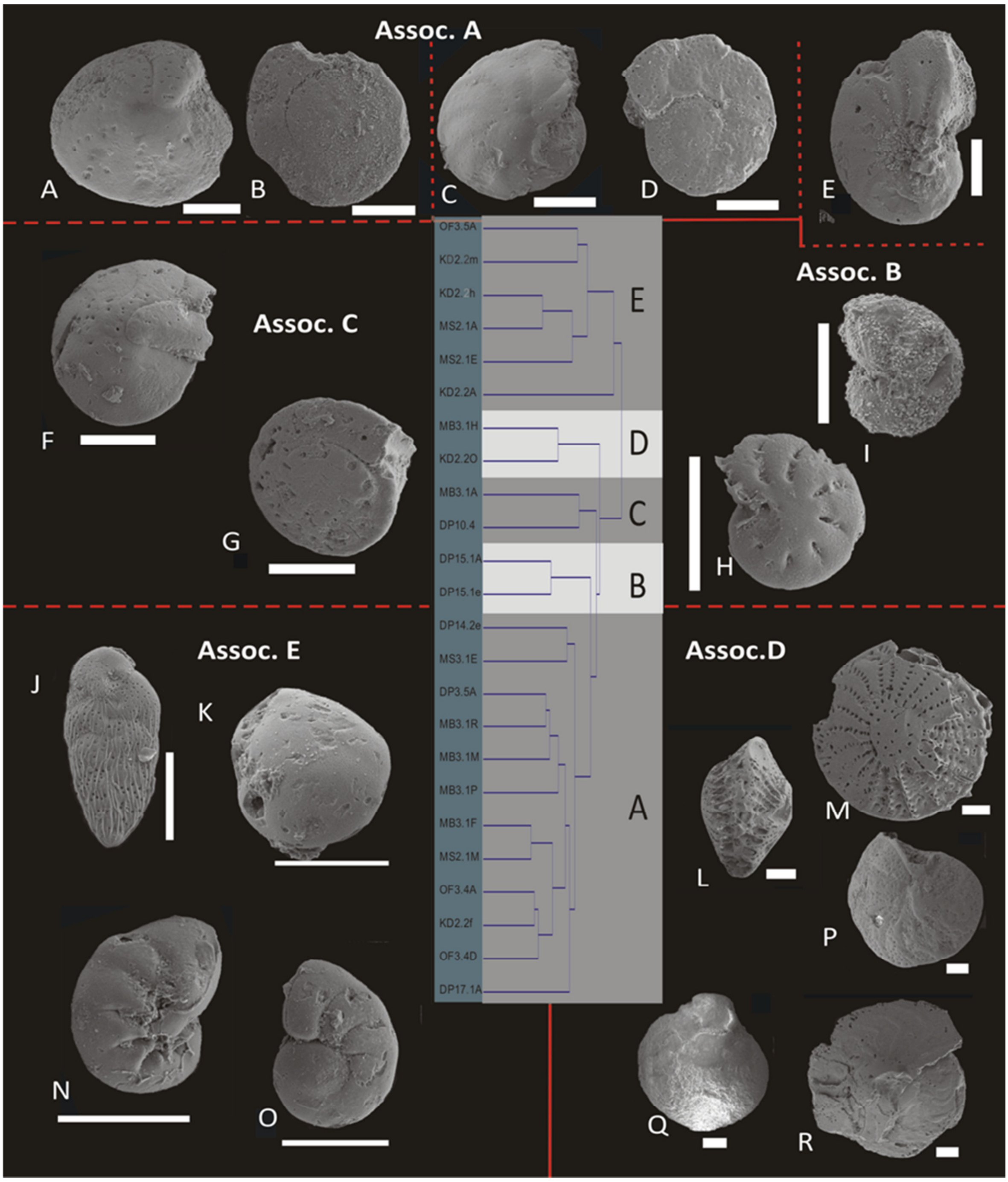


Figure 29. Key benthic foraminifera in Samples Associations produced by Bray-Curtis distance. Red hashed lines indicate foraminifera related to other associations. The five Sample Associations were selected by the author. Benthic foraminifera that characterise the associations are illustrated. All scale bars = 100µm. Red hash lines indicate foraminifera are associated to another cluster. A, B: *Cibicides temperata* C, D: *Cibicides perforatus* E: *Zeaflorilus stachei* F, G: *Cibicides molestus* H: *Elphdium advenum maorium* I: *Anomalinoides parvumbilia* J: *Bolivina finlayi* K: *Globocassidulina* sp. L, M: *Elphidium crispum crispum* N, O: *Zeaflorilus sp.* P, Q: *Cibicides thiaracuta* R: *Amphistegina* n. sp.

4.2.3 Sample Association C: *Cibicides temperata/ Cibicides molestus*

Two samples are placed in Sample Association C, sample MB3.1A and DP10.4 (Fig. 28). Both the samples have a stratigraphic age in the Otaian stage. Sample DP10.4 a fine calcareous sandstone from the Gowan Hill Sandstone and sample MB3.1A also was from fine calcareous sandstone of the Scargill Siltstone. Sample Association C has a moderately low diversity of species (Fig. 27) and a moderate to high evenness, in two of the samples it seems that there may be one species that is dominating (Fig. 27).

The two dominant species in the Sample Association are *Cibicides temperata* (Fig. 28) and *Cibicides molestus* (Fig. 29). The relative abundance of *C. temperata* in sample DP10.4 is c. 14% and in sample MB3.1A is c. 13%. The relative abundance of *Cibicides molestus* in sample DP10.4 was c. 12% and in sample MB3.1A the relative abundance was c. 1.2%. The *Globocassidulina* sp. (Fig. 29) was present in both the samples and the relative abundance was moderately high (Fig.28). Other species that are also included to form a moderate constituent of the faunal association include; *Bolivina finlayi* (5 – 10%) and *Cibicides novozelandicus* (5 – 10%) seen in Figures 28 and 29.

Palaeoenvironmental Indicators

The presence of *Cibicides* and the fine sandstone grainsize of the samples suggests a midshelf environment.

4.2.4 Sample Association D: *Elphidium/Cibicides* spp

The two samples in this cluster are KD2.2O (WR) a coarse grained limestone and MB3.1H (YS) coarse grained yellow sandstone from the Mount Brown Formation. Sample Association D has moderate evenness with a low to moderate diversity of species. The evenness of the Sample Association indicates that there is one species that is dominating the sample (Fig. 27). This is seen by the dominance of the species *Elphidium crispum crispum* (Fig.28).

The relative abundance of *E. crispum crispum* was c. 18% (KD2.2O) and c. 21% (MB3.1H). Elphidium advenum maorium also formed a high constituent c. 5.5% (MB3.1H) and c. 20% (KD2.2O) in relative abundance. *Elphidium* sp. were also large part of the association, the relative abundance of the species are c. 18.6% (MB3.1H) and c. 6.3% (KD2.2O).

The *Elphidium* sp. was unable to be identified down to species level due to abrasion of the test. The size of the species and shape of umbilicus suggests that they may be *Elphidium crispum crispum*. *Cibicides thiaracuta, C. temperata* and *C. perforatus* also form minor constituents to the faunal association (Fig. 28). The genera *Amphistegina* sp. and *Textularia* sp. were present in this association but only as a minor constituent (Fig. 28).

Palaeoenvironmental Indicators

Elphidium crispum crispum (Fig. 29) are typically found in shallow inner shelf environments; c. 0 – 30m (Hayward et al. 1997). When *E. crispum crispum* is found in high abundances > 70% they are living in a moderately sheltered, mid tidal – subtidal depths (0 – 2m), if they are moderately abundant they are typically found in environments of high to moderate energy at inner shelf depths (Hayward et al 1997). As the faunal abundance of this species decreases they have been known to occur from c. 50 - 200m water depths (Hayward et al 1997). In the samples *Elphidium crispum crispum* does not consist of >70% of relative abundance, the relative abundance of *Elphidium* present suggest mid shelf water depths.

The *Cibicides* genus has been found at water depths from 50 – 200m (Hayward 2004). *Cibicides thiaracuta* has a lifestyle where it lives attached to harder substrates or seaweed (per. Comms Reid 2010). *Amphistegina* and *Textularia* (Fig. 29) have proven to be reliable indicators of shallow water environments (Hayward et al. 2003) and are often associated in inner shelf environments c. 0 – 30m. When *Amphistegina* are present tend to indicate warmer water temperatures (Nelson and Cooke 2005).

4.2.5 Sample Association E: *Bolivina finlayi/Globocassidulina* sp.

There were six samples identified in this Sample Association as seen in Figure 28. Sample KD2.2A was taken from the Pahau Siltstone. Samples KD2.2m and KD2.2h are from the Scargill Siltstone. Samples MS2.1A and OF3.5A are from the Gowan Hill Sandstone. Samples MS2.1E is from the yellow sandstones of the Mount Brown Formation. The grain sizes in the samples were predominantly fine sandstone and siltstone. The overall diversity for Sample Association E is moderate to high indicating that there is no one dominant species (Fig. 27).

The most dominant foraminifer in this association is *Bolivina finlayi* (Fig. 28 and 29). The relative abundances within the samples ranged from c. 2.5 – 32%. The next most prominent species was *Globocassidulina* sp. where the relative abundance varied from c. 5 – 20.1%. A minor constituent of the faunal association was the species *Anomalinoides awamoana* which was associated with all the samples within the cluster. Other species in Sample Association E can be seen in Figure 28.

Palaeoenvironmental Indicators

Verhallen (1991) and Bernhard & Sen Gupta (1999) suggests that when faunas are strongly dominated by *Bolivina*, it is often indicative of low-oxygen, muddy environments. Modern relative abundances of *Bolivina* around New Zealand today, are suggested to have a broad modern range 2 – 850m and a mean range of 180 – 210m (Hayward 2004), indicating mid to outer shelf water depths.

4.3 Detrended Correspondence Analysis

Correspondence analysis (CA) is a technique that projects a multivariate dataset into two or three dimensions in an attempt to visualise trends and groupings within a large dataset (Hammer and Harper 2006). It is a method used to identify geographic trends and environmental gradients from taxonomic counts from a number of samples (Hill and Gauch 1980; Wartenburg et al. 1987; Hammer and Harper 2006).

CA tries to position samples and taxa in the same space so that it can be seen graphically as a scatter plot. The data produced in the scatter plot does not provide the environmental, geographical or sedimentary interpretation this must be determined by the researcher. There are two common problems associated with using CA; samples and taxa can be squeezed together at either end of the scatter plot and an arch effect (Hill and Gauch 1980).

The arch effect occurs when the primary environmental gradient is seen in both the first and second ordination axes (Hill and Gauch 1980; Hammer and Harper 2006). The samples also occur in an arch form, which can make plots difficult to read. The way to fix these problems is to run the samples and taxa by way of detrended correspondence analysis (DCA) which removes the arch effect and reduces the squeezing at either end of the scatter plots (Hill and Gauch 1980; Wartenburg 1987; Shi 1993; Hammer and Harper 2006).

DCA is a multivariate statistical technique that has been widely used particularly in ecology to determine environmental factors such as water depth. DCA deals with large data sets to display the interrelationships of data points (samples or taxa) in multidimensional space and to extract any major directions of data variation (Hammer and Harper 2006).

DCA was used to summarise and assist in the interpretation of the Miocene benthic foraminiferal data from the samples collected in the study area. The summary was produced in a two dimensional ordination plot and relates them to possible proxies. This was used to determine the benthic foraminiferal distribution patterns and to see if there were any environmental or sedimentary factors that were indicating the distribution. The scatter plot was compared to the Bray-Curtis Two way cluster analysis to see if there was a relationship between the data.

Data used for DCA was run four times in PAST© using data when:

- Rare species and planktic removed (Appendix 3, Figure 2)
- All Species included (Appendix 3, Figure 4)
- Rare species removed (Appendix 3, Figure 6)
- Benthic foraminifera >5% (Appendix 3, Figure 8)
- Benthic Families >1% (Appendix 3, Figure 10)

4.3.1 Detrended Correspondence Analysis Results: Sample Associations

The dendrogram produced from the cluster analysis using the Bray-Curtis method indicated five large foraminiferal Sample Associations as seen in Figure 28. The data used was rare species and planktics removed, other data produced from PAST© is seen in Appendix 3. Foraminiferal species were also plotted using DCA (Appendix 2) and grouped according to Species Associations as seen in Figure 28. The analysis found that the Sample Associations observed in Figure 28 relate well to the DCA (Fig. 29).

Figure 30 indicates that Sample Associations identified in cluster analysis are providing palaeoenvironmental information along axis 1 using DCA. The percentage of planktic and benthic foraminifera (Appendix 3, Figures 13-17) are also incorporated in Figure 30 provide further information on palaeoenvironment.

Coarser grain sizes tend to be to the far left along axis 1 this coincides with high benthic percentages (Fig. 31). Sample Association D had the coarsest grained samples and inner to mid shelf species of foraminifera. Sample Association A consisted of samples that had a range of grain sizes from sandy siltstone, fine sandstones to coarse grained limestone. The coarsest grained samples DP3.5A and MB3.1R tend to be to the left side of axis 1 and had high benthic percentages. The grain size of the samples decreases toward the right of axis 1 and the percentage of benthics tend to decrease with an increase in the amount of planktic foraminifera (Fig. 30).

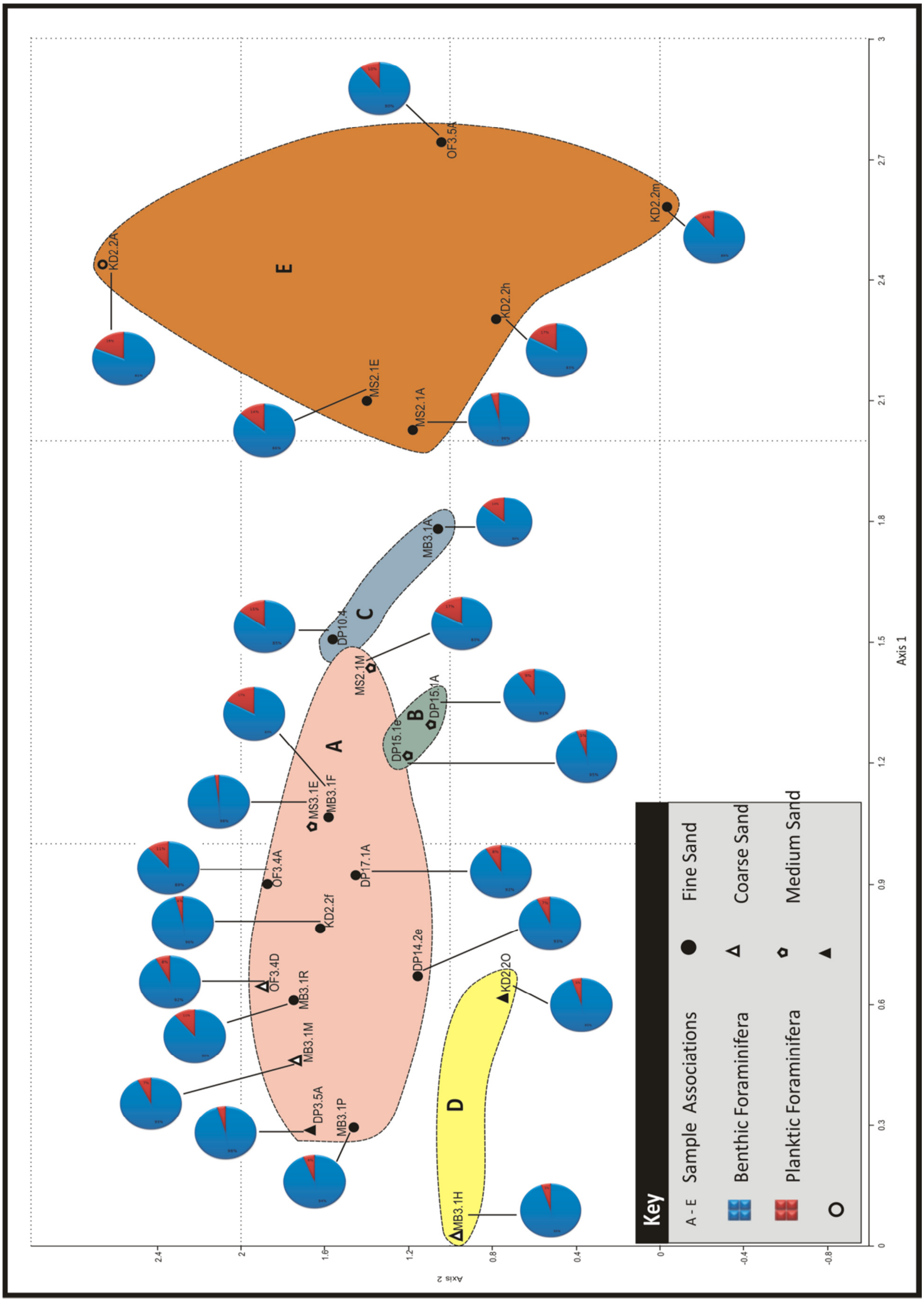


Figure 30. Detrended Correspondence Analysis with rare species and planktics removed. Pie charts are original planktic benthic percentages from the samples. Sample Associations are labelled A to E.

The grain sizes in Sample Association B were fine grained sandstone and an increase in planktic foraminifera percentage occurs along axis 1 (Fig. 30).

Sample Association C consisted of fine brown sandstones from the Gowan Hill Sandstone. The planktic: benthic percentages indicate that the water depth is increasing along axis 1 (Fig. 30). Sample Association D consisted of samples that were coarse grained from the Whiterock limestone. The samples low planktic: benthic percentages which indicate an inner shelf environment of water depths ranging from 0 – 30m.

The samples included in Sample Association E have the higher planktic percentages compared to the planktic percentages to the far left of axis 1 and Sample Associations A – D (Fig. 31). The grain sizes of faunal association E ranged from coarse silts to fine silty sandstone. *Cibicides temperata, C. perforatus* and *C. thiaracuta* are also seen in reduced numbers compared to Sample Association A and B and have an increase in the genus *Bolivina finlayi* and *Globocassidulina* sp. Indicating axis 1 is increasing in water depth to the right.

4.3.2 Species Associations

Species Associations were determined by Cluster Analysis and 11 Species Associations are identified (Fig. 28). The Species Associations were grouped into four Groups; W to Z (Fig. 31).

A. Group W: Species Associations 6 - 11

The species included within this group include; *Discorotalia aranea* (c. 1.5-3.8%), *Discorotalia tenuissima* (c. 3.4%), *Cribrotalia dorreeni* (c. 1.1 – 3%), *Anomalinoides macraglabra* (c. 1.5%), *Notorotalia spinosa* (c.1.1%), *Anomalinoides subnonionoides* (c. 1.3 - 2.3%) and *Lenticulina loculosa* (c. 1.1%), *Cibicides thiaracuta* (<5 – 9.9%), *Elphidium crispum crispum* (<5 – 24.9%), *Elphidium* sp. (<5 – 19.9%) and other species.

The genus *Discorotalia* has been identified at inner shelf water depths (Hayward 2004). *Notorotalia spinosa* and *Lenticulina* are interpreted to be from inner shelf to mid shelf environments (Hayward 2004). The samples that lie within the group consist of fine to coarse sandstones, predominantly coarse sandstone (Fig. 31). Group W appears to be overlapping in Group X and Y. The species associated with this Group tend to be inner to mid shelf species of foraminifera. The water depth range of *Elphidium crispum crispum* has been discussed in previous sections of this chapter.

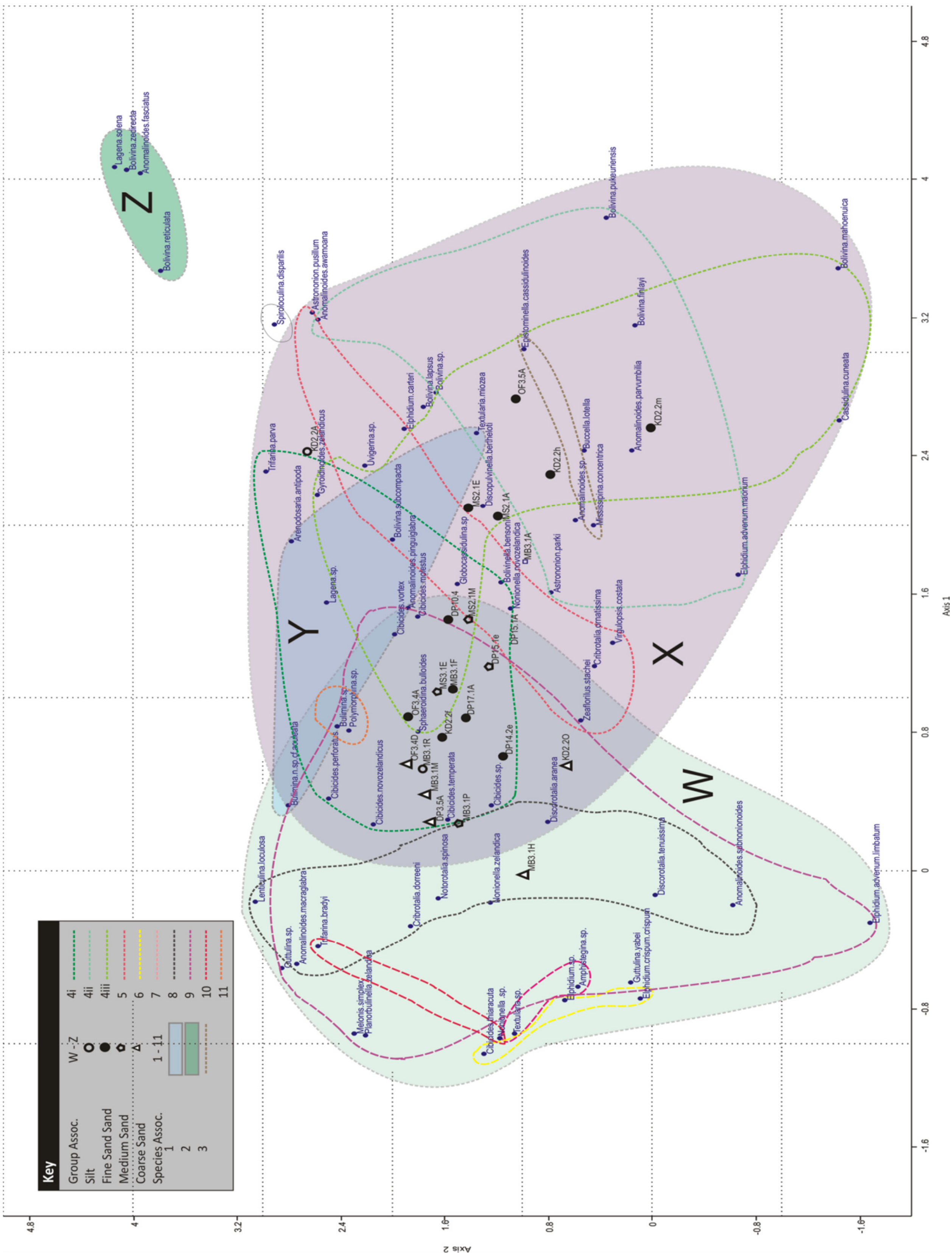


Figure 31. Detrended Correspondence Analysis of benthic foraminifera indicating Species Associations and four main Groups (Planktic and Rare species removed).

B. Group X: Species Associations 1, 3 – 5

Group X has Species Association 1, 3, 4 and 5 overlapping, the species relative abundance can be seen in Figure 28, Cluster Analysis diagram and in Figure 31. Water depths for the genus Cibicides and Bolivina have been discussed in earlier sections. *Anomalinoides parvumbilia* (1.2 – 13.7%) is known to indicate water depths ranging from 20 – 100m (Hayward and Brook 1994). *Cassidulina cuneata* (1.2 – 8.4%) is present toward the right end of axis 1 (Fig. 31) and *Discopulvinella bertheloti* (Fig. 31) is located to the mid-section along axis 1 and axis 2. The genus *Cassidulina* has been noted for having long ranging water depth of 40 – 850m (Hayward 2004). *Discopulvinella bertheloti* are known to have an extensive water depth range of 50 – 550m (Hayward et al 2003).

The genus *Nonionella* are associated with mid shelf to deep outer shelf environments c. 40 – 400m water depth (Hayward and Brook 1994; Hayward 2004), *Bolivina subcompacta* and *Cribrotalia ornatissima* when associated together are reliable indicators of shallower water depths (Hayward et al 2003). The genus *Textularia* are typically found in mid to inner shelf environments (Reid 1998; Hayward et al 2003). The abundance of *Nonionella* indicates that they were present in relatively quiet water conditions (Hayward and Brook 1994). The genus *Uvigerina* is typically found in midshelf water depths down to the outer shelf break (Reid 1997; Hayward 2004).

C. Group Y: Species Association 1

Group Y is related to Species Association 1 (Fig. 31) which consists of *Bulimina* n. sp. cf. *aculeata, Lagena* sp., *Textularia miozea*, *Cibicides vortex* and *Arenodosaria antipoda*. Group Y overlaps with Species Association 4i – iii predominantly and Group X (Fig. 31). The species relative abundances were less than 5% and only identified in five samples which were fine grained sandstones (Fig. 28).

The water depths that the genus *Cibicides* are typically found in has been discussed in previous sections in this chapter. The three other species in the Species Association have been identified at mid to outer shelf water depths. Group Y overlaps within the previous group mentioned and the benthic foraminifera within the group indicate that these fauna are found in mid shelf depths.

D. Group Z: Species Association 2

Group Z is the outlier in the scatter plot and is related to Species Association 2 (Fig. 28 and Fig. 31) the benthic fauna within the group are found at mid to outer shelf depths. Fauna associated with this group are from Species Association 2 and occur predominantly within Sample Association E. There are four benthic species within the cluster; *Bolivina zedirecta, Bolivina reticulata, Lagena solena* and *Anomalinoides fasciatus*. *Bolivina zedirecta* and *Bolivina reticulata* represent c.10.4 - 11.4% in the group. When the overall diversity of *Bolivina* is low, the depth range is between 180 – 280m (Hayward et al 2003).

4.4 Summary

DCA scatter plots of Sample Associations used indicate that axis 1 is related to grain size (Fig. 30). The coarsest samples DP3.5A and KD2.2O are to the left of axis 1 seen in Figure 30. The finer grained samples KD2.2A are to the right along axis 1 (Fig. 30). Medium grained samples are seen toward the middle of axis 1.

The DCA plots also indicate there is the influence of water depth along axis 1, based on benthic: planktic percentages. The higher planktic percentages were toward the right of axis 1 and related to samples KD2.2A, KD2.2h and KD2.2M (Fig. 30), the samples are finer grained and related to Sample Association E (Fig. 28). The lower planktic percentages were associated with Sample Association A and D, occurring to the left of axis 1 (Fig. 31).

The DCA scatter plots when looking at Species Associations and comparing with the samples identified that inner shelf species such as; *Elphidium crispum crispum* occur to the left of axis 1 (Fig. 31). Samples that are coarser grained also occur in the same area along axis1.

Environmental or sedimentary factors that may be influencing axis 2 are less clear. Species at the top and bottom in each group and Sample Association were investigated (Fig. 31). The genus *Cibicides* and *Buccella* have an attached mode of life and are epifaunal species. *Cibicides* are located mid-way up axis 2 and *Buccella* is located toward the bottom of axis 2. *Bolivina* and Bulimina are infaunal species that occur up and down axis 2. Indicating that axis 2 is not related to whether the foraminifera have an epifaunal or infaunal lifestyle in the sediment.

Overall axis 1 is interpreted to be related to water depth from inner shelf to upper outer shelf water depths. It is also inferred that axis 1 was related to the grain size of the samples. Environmental or sedimentary influences were undetermined.

Chapter 5

Discussion

The Tertiary sequence in North Canterbury provided a number of proxies that enabled biostratigraphic and palaeoenvironmental interpretations of the Waikari and Mount Brown formations. This chapter will combine evidence from lithostratigraphy, biostratigraphy, cluster analysis and detrended correspondence analysis to interpret the palaeoenvironments and palaeogeography in the Early Miocene.

5.1 Age Correlation

The biostratigraphy of the sections examined was based on benthic foraminifera. Planktic foraminifera were also used but were low in relative abundance in samples. The New Zealand Biozones in biostratigraphy are defined by planktic foraminifera (Hornibrook et al. 1989). The relative abundance in the samples from the Waikari and Mount Brown formation was low; the small amount of planktics that were identified were long ranging species that were not useful in age correlation, however some were useful based on first appearance datum and last appearance datum.

Key species of foraminifera identified in the study that had short stratigraphic age ranges for determining an Otaian age included; *Ehrenbergina marwicki* (Fig. 20A), *Guttulina yabei* (Fig. 20H), *Bolivinella bensoni* (Fig. 20B), *Textularia semicarinata, Uvigerina miozea* and *Melonis simplex* (Fig. 20F, G).

Many of the species identified in the Mount Brown Formation were long ranging species that needed correlation with first appearance datum and last appearance datums. Key first appearance datum in the Mount Brown Formation included; *Textularia miozea, Cibicides thiaracuta* (Fig. 20K, L), *Discorotalia aranea* (Fig. 20J), *Discorotalia tenuissima* and *Bolivina zedirecta* (Fig. 20E).

5.1.1 Waikari Formation Stratigraphic Ages

The age of the Waikari Formation was found to be Otaian. The Pahau Siltstone is the oldest of the three members identified in this study, based on its stratigraphic position with the other two members.

Key species identified in the sample included *Bolivina pukeuriensis, Bolivinella bensoni* and *Globorotalia minutissima*. The age for the Pahau Siltstone correlates with the ages identified by Andrews (1968). Key species identified in the Scargill Siltstone included; *Bolivina bensoni, Bolivina pukeuriensis* and *Globorotalia minutissima* which correlated with an Otaian age. The Gowan Hill Sandstone also had key species that included; *Polymorphina waitakiensis* (Fig. 20D), *Guttulina yabei* (Fig. 20H), *Plectofrondicularia proparri, Ehrenbergina marwicki* (Fig. 20A) and *Uvigerina miozea.* The Scargill Siltstone and Gowan Hill Sandstones were also determined to be Otaian in age.

Outside of the study area, to the north east in the Mandamus – Dove River area of North Canterbury, foraminifera samples from the Pahau Siltstone indicates an age of Waitakian to Otaian Stage (Sevon 1968). In the south east near the base of Mount Grey the stratigraphic ages for the Waikari Formation were determined to be Otaian, from data from the Kowai I Well (Edwards et al 1978).

5.1.2 Mount Brown Formation Stratigraphic Ages

The Mount Brown Formation includes the yellow sandstones, and the members Whiterock Limestone, Onepunga Shell Beds, North Dean Limestone and the Red Crag Limestones.

The age of the Whiterock Limestone was found to be Otaian in age and represents the oldest limestone from the Mount Brown Formation. Edwards et al. (1978) also determined the age of the basal Mount Brown Formation to be upper Otaian in age. The remaining limestone members and yellow sandstones were determined to be Altonian in age.

5.2 Palaeoenvironments

5.2.1 Waikari Formation

The Otaian deposits of the Waikari Formation are fine calcareous siltstone and fine sandstone. The Waikari Formation identified is thickest to the west in the study area. The depositional setting of the Waikari Formation proposed by Andrews (1968) was a simple, partially enclosed sedimentary basin, trending SSW – NNE. In this study the southwestern region of the basin was examined. The deepest part of the basin was determined by Andrews (1968) to occur to the north east of Waikari and the inner shelf edges occur to the south west of the study area toward Okuku and Karetu River (Andrews 1968, McCulloch 1981).

5.2.2 Palaeoenvironment Otaian Stage

Pahau Siltstone

During the Otaian stage the Pahau Siltstone was deposited in a mid to upper outer shelf water depths in the study area (Fig. 32A). Thicknesses of the Pahau Siltstone seen in the study area were thin. The presence of *Zoophycos* and *Ophiomorpha* observed in the Pahau Siltstone indicate mid to outer shelf water depths (Gaillard and Rachebouef 2006; Woods and Hansen 1985, Ekdale and Lewis 1990; Zonneveld et al. 2001). The higher relative abundance of *Zoophycos* also indicates a quiet, stable depositional environment.

Foraminifera identified in samples from the Pahau Siltstone are included in Sample Association E; *Bolivina finayi/Globocassidulina sp*. The presence of *Bolivina finlayi* in moderate to high numbers is indicative of a low-oxygen, muddy depositional environment during deposition of the Pahau Siltstone. The amount of planktic foraminifera identified in the Pahau Siltstones was higher compared to other members of the Waikari Formation (c. 4 – 18%) indicating greater water depths than the other units. The higher percentage of planktic foraminifera in the Pahau Siltstone is indicative of mid to upper outer shelf water depths.

Detrended Correspondence Analysis (DCA) indicated that along axis 1 there was a decrease in grain size with coarser samples to the left and finer samples progressing to the right along axis 1 seen in Figure 30. The Pahau Siltstone samples occur to the right along axis 1 that correlates with species identified in the samples and seen in Figure 31.

The Pahau Siltstone lacks well preserved macrofossils, however fragments that were identified typically occur at midshelf depths. The reason for the lack of preservation could be due to dissolution during burial of biologic remains. The presence of *Zoophycos* indicates other fauna may have been present.

Overall based on sedimentology, tracefossils, macrofossils and foraminiferal components the Pahau Siltstone was deposited in a mid to outer shelf environment.

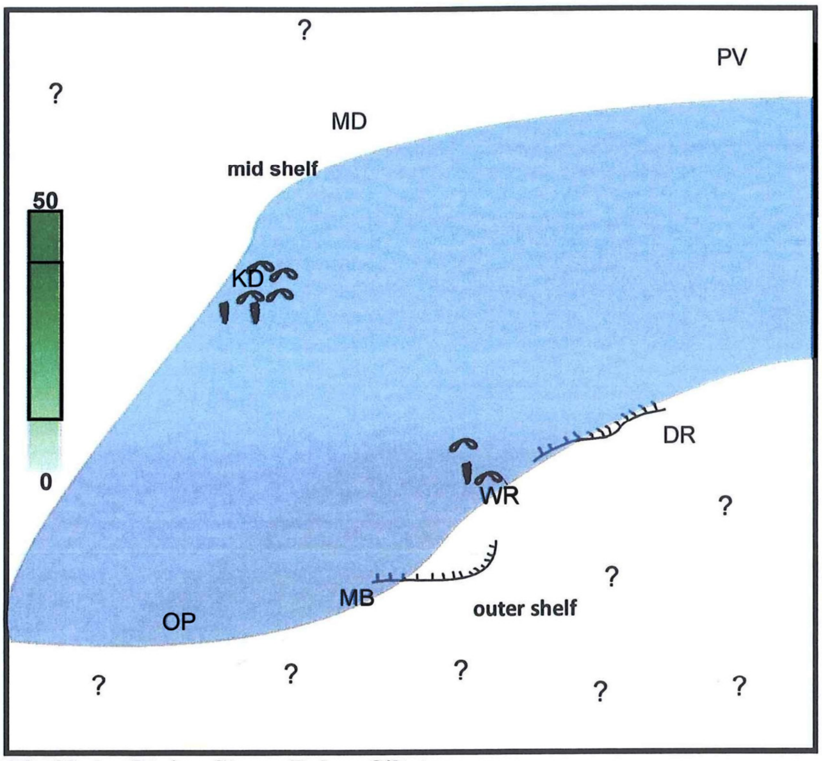


Fig 32-A. Otaian Stage; Pahau Siltstone

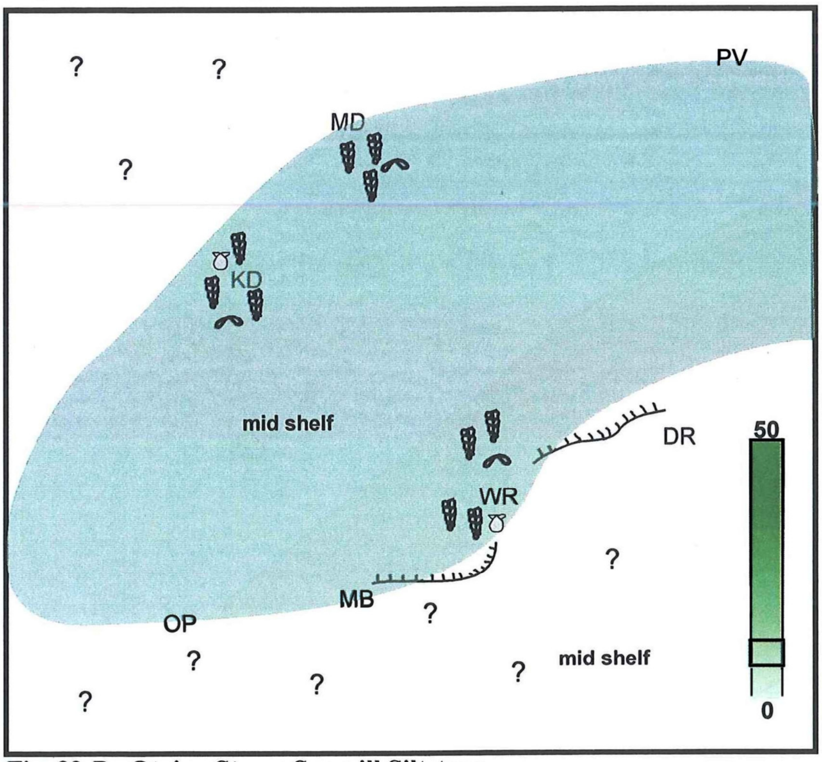


Fig. 32-B. Otaian Stage; Scargill Siltstone

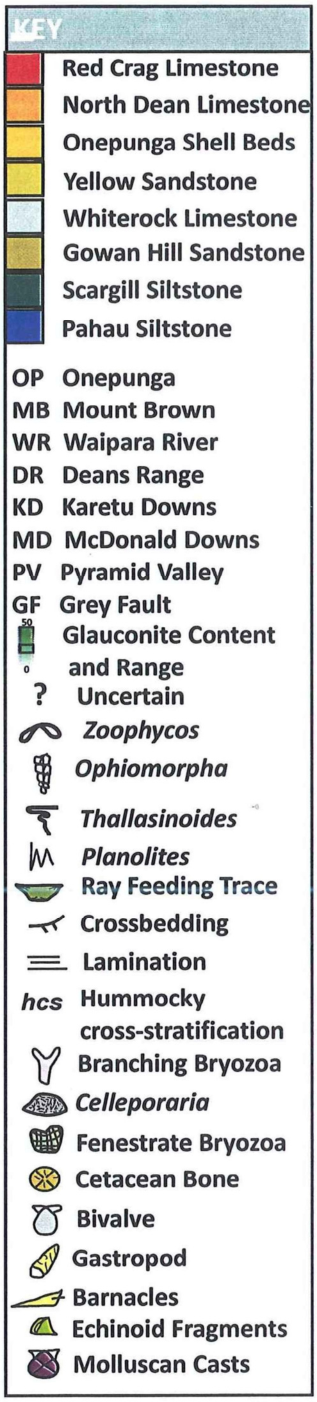


Figure 32. Palaeoenvironment and palaeogeography interpretation of Waikari and Mount Brown formation members; A: Pahau Siltstone; B: Scargill Siltstone; C: Gowan Hill Sandstone and Whiterock Limestone; D: Yellow sandstones and Onepunga Shellbeds; E: Yellow Sandstones and North Dean Limestone; F: Yellow sandstone and Red Crag Limestones.

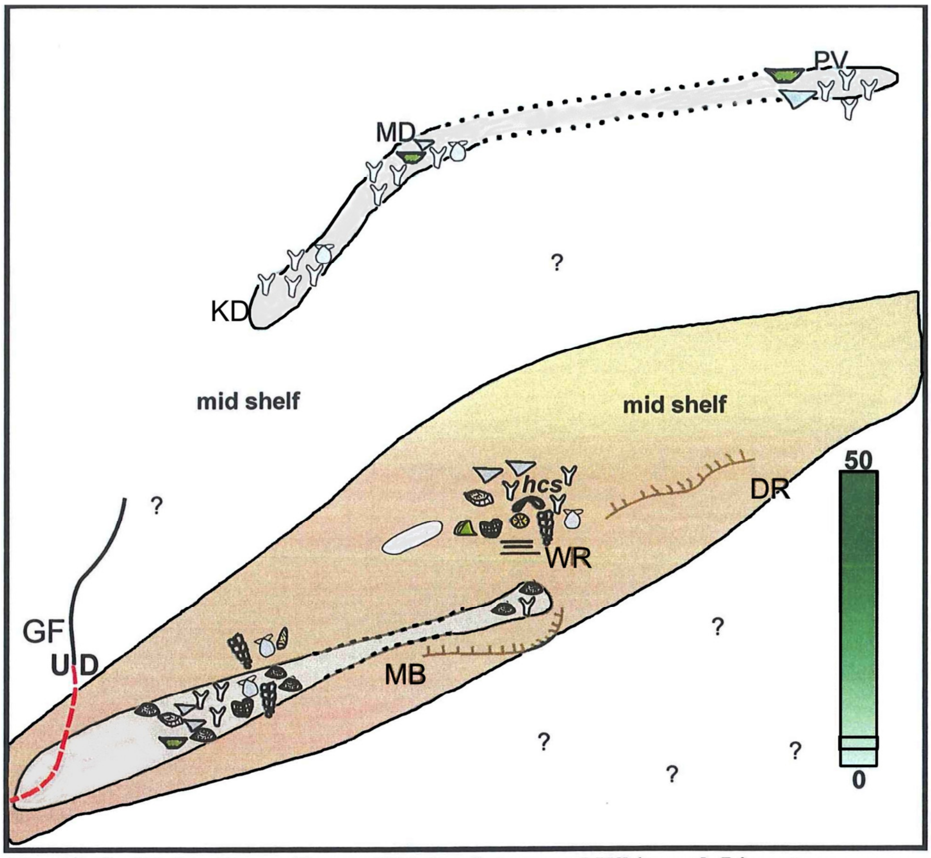
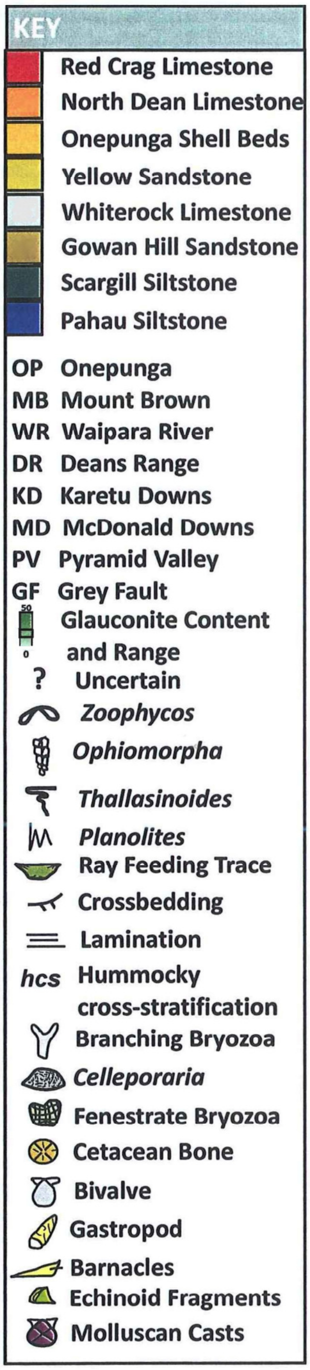


Fig. 32-C. Otaian Stage; Gowan Hill Sandstone and Whiterock Limestone



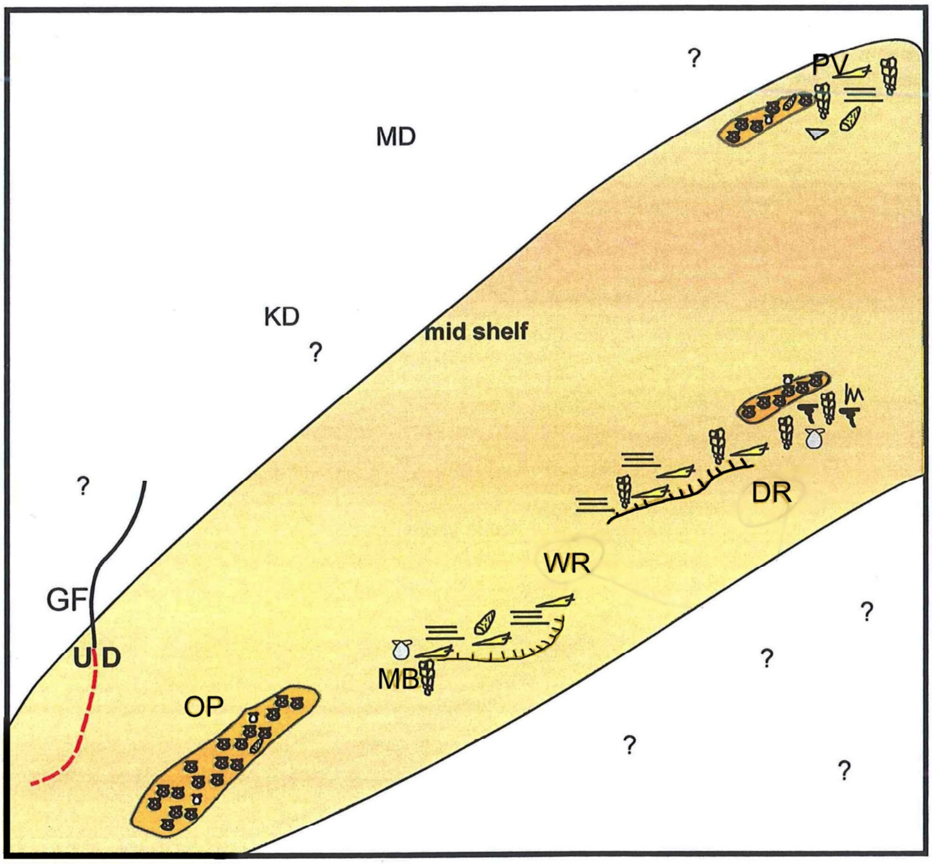


Fig. 32-D. Altonian Stage; Yellow Sandstone and Onepunga Shell Beds

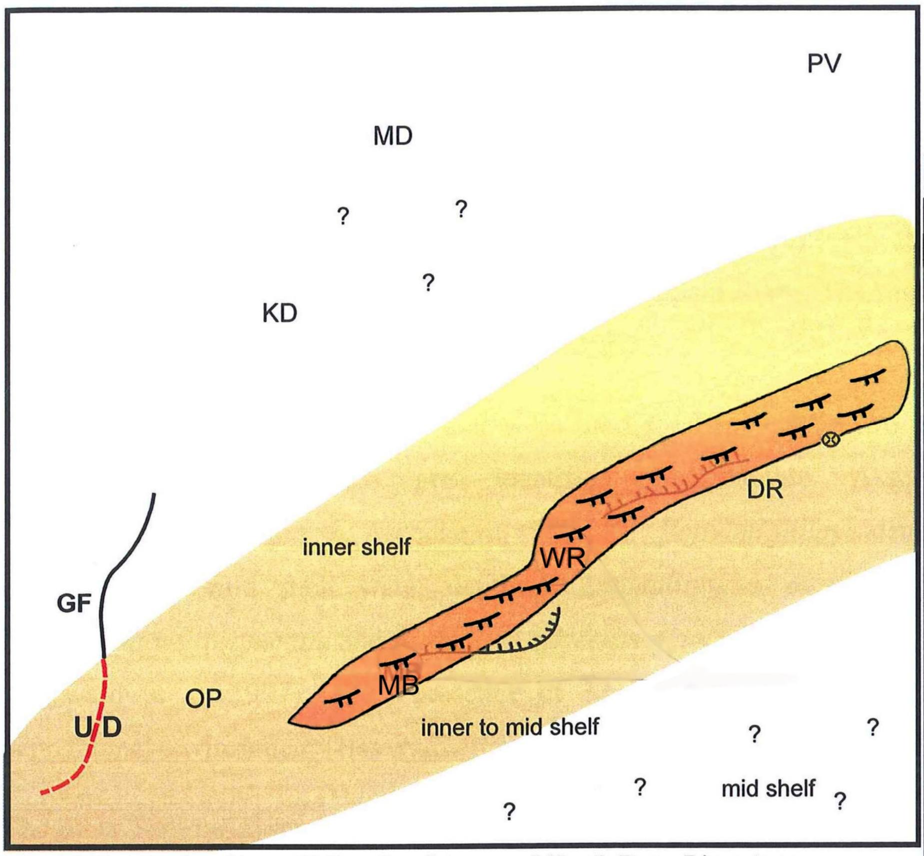
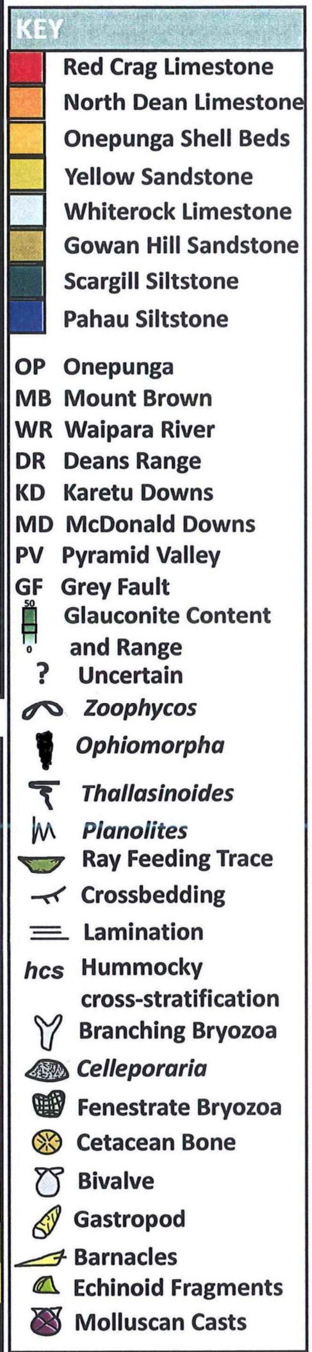


Fig. 32-E. Altonian Stage; Yellow Sandstone and North Dean Limestone



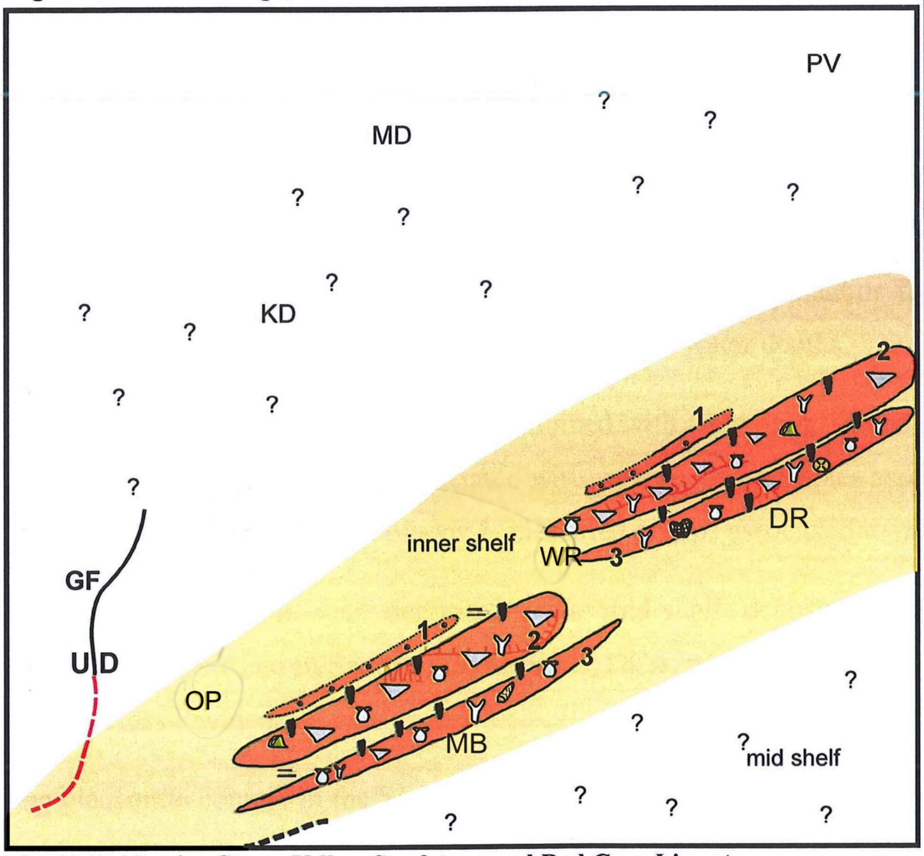


Fig. 32-F. Altonian Stage; Yellow Sandstone and Red Crag Limestone

<u>Scargill Siltstone</u>

The Scargill Siltstone, a member of the Waikari Formation, is widespread in the North Canterbury region (Fig. 2). Andrews (1968) found that the siltstone extended from the north west of the study area and is seen in locations toward the east coast of North Canterbury, and further north into the Kaikoura region (Rattenbury et al. 2006). The thickest units of Scargill Siltstone in this study occur at Karetu Downs, in Waipara River. The thickest units identified by Andrews (1968) occur to the north east of Waikari.

The samples of Scargill Siltstone that were used for Bray-Curtis two way cluster analysis of foraminifera predominantly are identified in Sample Association E; *Bolivina finlayi/Globocassidulina sp.* Association (Fig. 28). *Bolivina finlayi* identified in the association are typical of mid shelf water depths. *Anomalinoides parvumbilia, Astrononion parki*, *Anomalinoides awamoana* and *Elphidium advenum maorium* are found at mid shelf water depths (Hayward et al. 1997). The presence of *Elphidium advenum maorium* indicates a quiet depositional environment (Hayward et al. 1997).

The other Sample Association the Scargill Siltstones were identified in was Sample Association A. This association was dominated by mid shelf species like *Cibicides perforatus* and *Cibicides temperata*. The two Species Associations of 4i and 4ii (Fig. 31 and 32) indicate mid shelf environments based on the presence of *Cibicides perforatus, Cibicides temperata, Trifarina parva, Elphidium advenum maorium, Bolivina finlayi* and *Anomalinoides parvumbilia*.

The planktic foraminifera that were present in Scargill Siltstone samples ranged from c. 8.2 to 17% along the DCA plot (Fig. 30). The lower percentage of planktic foraminifera occur to the left of axis 1, along with grain size indicates mid shelf water depths.

The grain size of the Scargill Siltstone combined with DCA (Fig. 30 and 31) indicates species of foraminifera and grain size are associated with water depth. Samples associated with the Scargill Siltstone are plotted to the left of axis 1, identified groups associated to mid-shelf environments.

The Scargill Siltstone was deposited in a mid-shelf depositional environment based on foraminifera identified in Sample Associations, DCA, planktic: benthic percentages, macrofossil and tracefossil evidence.

The glauconite content in the Scargill Siltstone is c. 5 – 10% compared to the Pahau Siltstone of c. 10 – 30%. The increased emergence of the trace fossil *Ophiomorpha* seen in the Scargill Siltstone and a reduction of the trace fossil *Zoophycos* indicate a shallowing to mid-shelf water depths during deposition of the Scargill Siltstone. The number of macrofossils preserved in the Scargill Siltstone and contained fauna that are seen at mid shelf depths, below fair weather wave base and require low to moderate sedimentation rates. These included; *Lentipecten hochstetteri,* fenestrate bryozoa and branching bryozoa.

During the late Otaian Stage the Gowan Hill Sandstone was deposited in a limited geographic area through the Waipara – Waikari region in a mid-shelf environment. The thickest accumulation of the Gowan Hill Sandstone occurs in the Waipara River Section (Fig. 2) and thins to the south east and north east of the study area.

The sediments are coarse calcareous siltstones and fine grained calcareous sands with a higher amount of bioclastic material compared to the Pahau Siltstone and Scargill Siltstone. The glauconite content is lower (c. 3 – 5%) compared to the Pahau Siltstone and Scargill Siltstone. This suggests that there was a change in depositional environment during the late Otaian.

The change from mid shelf to upper outer shelf during deposition of the Pahau Siltstone to a mid-shelf environment during deposition of the Scargill Siltstone, this is indicated by a reduction in glauconite content (Fig. 32B), indicating closer to source and an increase input of terrigenous sediment. The trace fossil dominance changes from *Zoophycos* to *Ophiomorpha* dominated trace fossil assemblage, and the preservation of larger macrofossils indicates mid shelf depositional environment.

<u>Gowan Hill Sandstone</u>

Samples taken from the Gowan Hill Sandstone consisted of foraminifera indicating a mid-shelf environment, these include; *Cibicides temperata, Cibicides perforatus, Globocassidulina sp., Cibicides novozelandicus, Cibicides molestus.* The foraminifera identified are related to Sample Association A; the *Cibicides temperata/Cibicides perforatus* Sample Association. The high relative abundance of *Cibicides* indicates a mid-shelf environment.

The DCA analysis identified axis 1 was related to grain size and water depth (Fig. 31) the planktic:benthic percentages are compared with the samples from the Gowan Hill Sandstone it is found there is a correlation with the amount of planktics in the samples. The planktic percentage ranged from c. 8.8 – 11.9%. Which is lower compared to the Pahau Siltstone and Scargill Siltstone.

At middle Waipara River, a mechanism for the alternating deposition of siltstones and sandstones are periodic storm events, which is also suggested by Andrews (1968). Evidence for storm events during deposition of the Gowan Hill Sandstone seen during this study includes; hummocky-cross stratification, broad channel, rip up siltstone clasts and discontinuous horizons of predominantly branching bryozoans.

Hummocky cross-stratification observed in the Waipara River indicates periodic storm events where wave action reached below fair weather wave base. Bryozoa occur at mid shelf water depths, below fair weather wave base and prefer a low energy environment (Reid 2010). During a storm when waves reach below the fair weather wave base, colonies of branching bryozoa can become disturbed or destroyed on the seafloor, once the storm eases bryozoans can re-establish on the substrate.

The broad channel is distinguished by the macrofossils observed within the channel. These include; brachiopods, fenestrate bryozoa, encrusting bryozoa and cetacean bones. Carbonaceous material is identified around the fenestrate bryozoan and brachiopods in the broad channel indicating small influxes of terrestrial material during storm events got trapped in fenestrate bryozoa. The brachiopod horizon seen in Figure 6B was not in life position indicating transportation from further up the shelf.

In the McDonald Downs area, the Scargill Siltstone goes straight to Whiterock Limestone and the Gowan Hill Sandstone is missing. The Gowan Hill Sandstone occurs along a band along the Deans Range (Fig. 32C) between the Scargill and Whiterock Limestone, indicating a localised submarine high that saw laminations and hummocky cross stratification and sediments of the Gowan Hill Sandstone laid down before the Whiterock Limestone.

Whiterock Limestone

During the late Otaian Stage toward the south eastern limit of the study are the oldest limestone (Whiterock Limestone) in the Mount Brown Formation was deposited. The thickest accumulation of the limestone occurs at the south eastern end of Mt. Grey, Whiterock (Fig. 2). The limestone beds have ‘thickets’ of bryozoan-brachiopods best seen at Onepunga (Fig.2).

Bryozoans identified in the Whiterock limestone included; *Celleporaria papillosa*, branching bryozoa, fenestrate bryozoa, encrusting bryozoa. Bryozoans are typically found at mid shelf water depths, low energy, cool water environments (Nelson 1978; Nelson et al 1988; Reid 2010). The Whiterock Limestone is a typical non-tropical cool-water, carbonate deposit that is frequently seen in New Zealand, Oligocene Limestones (Nelson et al 1988; Nelson and Cooke 2001). The abundance of bryozoans in the Whiterock Limestone is similar to bryozoan dominated lithofacies off the modern New Zealand continental shelf (Nelson et al. 1988). Which are similar to bryozoan dominated lithofacies seen in the New Zealand Cenozoic rock record (Campbell et al 1988, Taylor 2004).

The bryozoan, *Celleporaria papillosa* is abundant through the middle section of the Whiterock Limestone. Palaeoenvironmental facies that the *Celleporaria* has been identified in occurs on sandy and shelly bottoms, typically at depths of 30 to 60m (Moisette et al. 2007). The modern *Celleporaria* in New Zealand water are found at water depths down to 690m and a mean depth of 214m (Taylor et al. 2004).

The modern bathymetric distributions of bryozoans suggest that the encrusting bryozoan that lives attached to hermit crabs or gastropods as seen in Figure 9D, has a modern water depth ranging from 0 – 252m the mean water depth for modern day species was 104m, it is found when the hermit crabs occur at low latitudes they are found at shallower depths (0 – 40m) and higher latitudes occur further down the shelf at around 100m (Taylor et al. 2004). In modern environments the bryozoan is found offshore the South Island (Taylor et al. 2004). Occurrences' of the encrusting bryozoans are typically seen in the Red Crag Limestones, Whiterock Limestone, Clifden Limestone, Southland, Winton District (Taylor et al. 2004).

The deposition of the Whiterock Limestone occurred in an inner to midshelf environment. The abundance of bryozoa indicates depths greater than 50m as they require non-turbid environments.

Trace fossils are often effectively used as an aid to palaeoenvironmental interpretations. The stratigraphic utility of trace fossils significance varies (Pemberton and MacEachern 2005). The feeding trace *Pisichnus* was identified in two locations in the Whiterock Limestone; Onepunga and McDonald Downs. When the trace *Pisichnus* is identified in sandier facies like the Whiterock Limestone are found in shallow water depths (Gregory 1991). The foraminifera *Elphidium crispum crispum* was identified from Whiterock Limestone samples and also indicates inner shelf water depths. The trace fossil *Ophiomorpha* was observed at Onepunga indicating inner to mid shelf sandy depositional environment.

Cluster analysis identified the samples from the Whiterock Limestone in Sample Association D (Fig. 28). The palaeoenvironmental water depths indicate inner to mid shelf water depths based on the relative abundance of *Elphidium crispum crispum, Elphidium spp.* and *Cibicides thiaracuta.* The genus *Amphistegina* were also present which are indicator of a shallow water environment (Hayward et al. 1997). The planktic percentages of the foraminifera from the Whiterock Limestone samples were low (c. 5 and 7.6%) further indicating shallower water depths. The DCA plot placed the coarser grained Whiterock Limestones to the left along axis 1 (Fig. 29) indicating shallow water depths. The species associated with the samples were identified in Species Associations 6 and 7 in Group W (Fig. 30) which foraminifera with water depth ranges of inner to mid shelf. These included; *Discorotalia tenuissima, Cribrotalia dorreeni, Anomalinoides macraglabra, Planorbulinella zelandica* and *Discorotalia aranea.*

The Whiterock Limestone appear interbedded with mid shelf deposits of the Gowan Hill Sandstone indicating a submarine high. Andrews (1968) suggested the accumulation of the bryozoan beds that make up the Whiterock Limestone occurred on a submarine basement high.

The thicker accumulation of Whiterock Limestone and lower amounts of terrigenous material at Onepunga deposits suggests that the establishment of the bryozoan colony first occurred in a more stable, quiet, sheltered environment at inner to mid shelf water depths.

The deposition of the Waikari Formation suggests a progressive shallowing from an upper outer shelf environment during deposition of the Pahau Siltstone, to mid shelf deposition of the Scargill Siltstone and an upper mid shelf environment during the deposition of the Gowan Hill Sandstone (Fig. 32 A-C). The deposition of the Whiterock Limestone occurred in the late Otaian stage on a submarine high in an inner to mid shelf environment (Fig. 32C).

5.2.3 Palaeoenvironment in Altonian Stage

In summary, sedimentary structures, bryozoans, bivalves, brachiopods, trace fossils and foraminifera determine a mid to inner shelf depositional environment for the Mount Brown Formation. The Mount Brown Formation consists of the members; yellow sandstone, Whiterock Limestone, Onepunga Shell Beds, North Dean Limestone and the Red Crag Limestones.

The yellow sandstones were deposited in a mid shelf environment with limestones (Onepunga Shell Beds, North Dean Limestone and Red Crag Limestones) interbedded in the sandstone.

The yellow sandstone indicates a midshelf depositional environment that was subject to wave action periodically based on laminations observed on Mount Brown and along the Deans Range (Fig. 32D-F).

Macrofossils seen in the yellow sandstone include; *Balanus,* fenestrate bryozoa, *Ostrea,* encrusting bryozoa, *Pecten* and *Lentipecten hochstetteri*. The presence of *Balanus* indicates a seafloor which had moderate current action, which is required for barnacles as they are filter feeders (Kamp et al. 1988; Beu et al. 1980).

Trace fossils identified in the yellow sandstone indicate mid shelf water depths. At North Dean, the trace fossils identified are *Thallasinoides, Ophiomorpha* and *Planolites*. *Planolites* extend down to sublittoral depths (Pemberton and MacEachern 2005). Investigations by Woods and Hansen (1985) investigated shallow water trace fossils and found that *Ophiomorpha* are typically seen in beach deposits that consist of well sorted, fine to very fine grained sandstones.

The planktic percentages from samples of the yellow sandstone were low (c. 2 – 15%). Cluster analysis identified the yellow sandstone samples in the Sample Associations A and B (Fig. 29). The foraminifera identified as mid shelf species included; *Cibicides perforatus, Cibicides temperata, Cibicides novozelandicus, Zeaflorilus stachei* and *Cibicides thiaracuta.*

Onepunga Shell Beds

During deposition of the yellow sandstones the Onepunga Shell Beds were being deposited in shell banks across the shelf. The Onepunga Shell Beds occur as discontinuous lenses along Deans Range and at Pyramid Valley (Fig. 32D). The discontinuous indicate areas where molluscs were able to become established and represent a death assemblage. The sandstone clasts identified near the base of the beds indicates periods of higher current energy ripping up clasts of yellow sandstone and depositing them at the base of the Onepunga Shell Beds. The lack of bryozoans in the shell beds indicates a slightly higher energy environment than one would allow the bryozoa to establish themselves. The molluscan fauna suggest a warmer water environment (Beu and Maxwell 1990).

The sandstone clasts from the yellow sandstone appear to have been ripped up from the Mount Brown Formation indicating transportation further down the shelf but not as a debris flow suggested by McCulloch (1981). Based on the shell beds moderate to well sorted nature and the shell casts in line with the bedding. Winnowing of fines out of the shell beds occurred rather than transportation far down the shelf. The beds appear to represent a death assemblage of molluscan fauna.

North Dean Limestone

Deposition of the North Dean Limestone during the Altonian Stage indicates a change in depositional setting from to a higher energy depositional environment compared to the Whiterock Limestone and Onepunga Shell Beds. The North Dean Limestone was deposited in a warm, high energy environment at inner shelf water depths (Fig. 32E). The deposition of the limestone occurred along a limited geographic area trending from the south east to north east.

Bioclastic remains identified in the North Dean Limestone are similar to the fauna that were seen in the Red Crag 2 and 3 Limestones. Foraminifera identified using Bray-Curtis two way analysis suggested the limestone was deposited in an inner shelf environment based on the presence of *Amphistegina sp.*, *Elphidium crispum crispum* and *Cibicides thiaracuta*. The presence of *Amphistegina sp,* is associated with warm inner shelf water depths (Hornibrook et al. 1989).

Cluster analysis placed the North Dean Limestone sample into Sample Association E which is related to inner to mid shelf foraminifera. The coarse grained nature and low planktic percentage (c. 4.3%) indicate inner to mid shelf environments (Fig. 30 and 32E). The North Dean limestone foraminifera fauna relate to Group W which includes Species Associations 6 – 11 (Fig. 30) which includes the foraminifera *Discorotalia aranea, Cibicides thiaracuta, Elphidium crispum crispum* and *Cibicides thiaracuta.*

<u>Red Crag Limestone</u>

Subtle changes in faunal composition occur in Red Crag Limestone 2 and 3 reflect changes in environmental setting and a further shallowing along the shelf. Most notably is the increase in terrigenous material and increase grain size. The Red Crag Limestone 2 is dominated by *Pachymagus* which are associated in calmer water conditions. The *Pachymagus* has poor pedicle attachments which cannot tolerate high energy environments and high sedimentation rates (McCulloch 1981).

Fauna seen in the Red Crag Limestone 2 are clear water filter feeders (brachiopods, bryozoan and pectens). The palaeoenvironment suggested is one of a sheltered, sandy shore, inner to mid shelf environment. The presence of the traces *Ophiomorpha* and *Thalassinoides* are typical ofinner to mid shelf environments (Fig. 32F).

Between the Red Crag 2 Limestone and Red Crag 3 Limestone is a persistent band of yellow sandstone (Fig.16), bioturbation increases toward the top of the sandstone and continue into the Red Crag 3 Limestone. The increase bioturbation toward the top of the sandstone indicates a change in depositional setting which allowed the burrowers to colonise. The deposition of the Red Crag Limestone 3 was heavily bioturbated at the base which indicates a quiet, moderately low energy environment. Subtle faunal changes in the Red Crag Limestone 3 of larger *Pecten* faunal species, branching bryozoa, *Ostrea* suggest inner shelf to mid shelf, moderate energy environment energy (Fig. 32F).

McCulloch (1981) suggested that the increase of terrigenous material was the result of uplift which increased sediment supply into the basin leading to further shallowing of the basin and movement of the coast further to the east. The relative abundance of fauna identified in the Red Crag limestones and analysis of the fauna and high levels of terrigenous detrital material suggests an environment that was similar to the North Dean Limestone.

5.3 Palaeogeography

During the Early Miocene the Australian-Pacific plates were converging and changing the depositional setting of New Zealand from a passive margin to an active margin (King et al. 1999). Tectonic deformation in the region is associated with this onset which is reflected by facies changes in the Early Miocene deposits (Bradshaw 1975).

5.3.1 Waikari Formation

Initial onset of the Pacific-Australian plates did not affect the distribution of the Pahau Siltstone significantly. The inner shelf during deposition of the Pahau Siltstone was located to the north west of the study area (Fig. 32A). The terrigenous source for the Pahau Siltstone was inferred by Andrews (1968) to be coming from the northwest.

Continued convergence caused uplift and faulting in the Early Miocene which led to an increase in sedimentation and accumulation at the south western end of the basin described by Andrews (1963). This increased sedimentation and period of uplift brought the coastline toward the east and a change from an outer shelf depositional environment to a mid-shelf environment with the deposition of the Scargill Siltstone (Fig. 32B).

Uplift of the Grey Block in the south western region of the study area confined the depositional area of the Gowan Hill Sandstone along a band trending south west to the north east (Fig. 32C). During this period the accumulation of the Whiterock Limestone was accumulating predominantly south west of the region (Fig. 32C).

5.3.2 Mount Brown Formation

Deposition of the yellow sandstones indicates a change in depositional environment to predominantly mid shelf environment. The yellow sandstones accumulated in a mid-shelf setting toward the east. This convergence of plates led to the expansion of land areas in an eastward direction (King et al. 1999). Which is reflected by the mid shelf environments in the Altonian stage (Fig. 32 D-F).

Cooke and Nelson (2001) reconstructed the palaeogeography of the southern ocean in New Zealand and found that warmer waters extending further south. The warmer waters incurred a change in fauna from bryozoan dominated to molluscan dominated fauna which is reflected by the Onepunga Shell Bed fauna. The molluscs are typically associated with warmer water environments during the Altonian stage (Beu and Maxwell 1990).

The expansion of land areas is reflected in the depositional sequences seen in the study area particularly the deposits of the North Dean Limestone reflecting an inner to mid shelf high energy environment and occurring further toward the east, compared to the deposits from the Otaian stage. The Red Crag Limestones were deposited in an inner to mid shelf environment and occur to most eastern extent of the study area (Fig. 32F).

Chapter 6

Conclusions and Future Work

6.1 Conclusions

Early Miocene deposits in the Waipara-Waikari region represent a shallowing from outer shelf to inner mid shelf water depths. This is reflected in the sediments seen in the North Canterbury Region of the Waikari Formation and the Mount Brown Formation. Overall, the Waikari and Mount Brown formations reflect a change in depositional setting that was influenced by the onset of Australian-Pacific plate convergence leading to uplift, increase in land and sedimentation in the North Canterbury region. The Waikari Formation in the Waipara-Waikari study consists of three members; the Pahau Siltstone, Scargill Siltstone and Gowan Hill Sandstone. The relative stratigraphic age of the members were determined using foraminifera is Otaian Stage. The Mount Brown Formation consists of yellow sandstones and coarse limestones that were deposited in the late Otaian-Altonian stage.

The Pahau Siltstone is the oldest unit deposited in the Otaian Stage. The member is a highly glauconitic, blue grey-green, coarse silt, poorly sorted, moderately indurated, calcareous siltstone. Bray-Curtis cluster analysis and Detrended Correspondence analysis determined that samples from the siltstone were deposited at mid to upper outer shelf water depths during the Otaian Stage.

The Scargill Siltstone is a light blue-grey, coarse silt to very fine sand, moderately sorted, moderately indurated, massive calcareous sandy siltstone. Bray-Curtis analysis indicate deposition occurred in a mid-shelf environment based on correlation of grain size, foraminifera species and planktic: benthic percentages. The lack of sedimentary structures and moderate to high levels of bioturbation caused by *Ophiomorpha* indicate deposition occurred in a quiet environment, below fair weather wave base.

The Gowan Hill Sandstone consists of alternating beds of yellow – grey brown, calcareous, massive, silty sandstone and light blue – grey, calcareous, massive, sandy siltstone that were deposited during the Otaian stage. Bray-Curtis two way analysis identified the foraminifera and samples to be associated with a mid-shelf environment. The sedimentary structures are associated with mid shelf environments. The distribution and deposition of the Gowan Hill

Sandstone was restricted in the central part of the study area which indicates the influence of uplift and increased exposure of land to the west.

The Whiterock Limestone is interbedded with the upper units of the Gowan Hill Sandstone and are grey – cream, moderately to poorly indurated, poorly sorted, sandy calcarenite, bryozoan biosparite that was deposited during the Otaian stage. Trace fossils, macrofossil and interpretation of Bray-Curtis two way analysis indicates deposition of the limestone occurred in a mid-shelf environment. The limestone deposits reflect cooler water deposition which is characteristic of many New Zealand limestones.

The yellow sandstones are yellow-brown, moderately to poorly indurated, very fine to fine sand, moderate to well sorted, calcarenite. The yellow sandstones are determined to be Altonian in age based on foraminifera evidence. Trace fossil, macrofossil and Bray-Curtis interpretation determines deposition of the sandstones were at mid shelf water depths. The mid shelf is identified to further to the east which was influenced by Early Miocene uplift.

The deposition of the Onepunga Shell beds occurred in a warmer water depositional environment in shell banks based on a change of fauna from bryozoan dominated to molluscan dominated in a mid-shelf environment during the Altonian stage.

The North Dean Limestone was deposited at inner to mid shelf depths in a moderate to high energy environment. Bray-Curtis two way analysis and detrended correspondence analysis identified foraminifera associated with an inner to mid shelf warm water environment.

The Red Crag Limestones are a yellow-brown, fine to very coarse calcarenite, moderate to poorly sorted, moderate to very well indurated, massive; sandy quartz biosparite; that was deposited during the Altonian stage. The oldest of the limestones were deposited as lenses in an inner to mid shelf environment. The Red Crag Limestone 2 is the thickest deposit of the limestones and is dominated by inner to mid shelf fauna. Heavy bioturbation by *Ophiomorpha* indicates a mid-shelf environment.

6.2 Future Work

Work during this study found there is still a need for further work to be done in the North Canterbury region; with an emphasis on quantitative analysis of macrofossils and/or tracefossils identified in the Waikari and Mount Brown formations.

Detailed studies focusing on the palaeoecology and quantitative analysis of the macrofossils recognised in the Whiterock Limestone, Onepunga Shell Beds and Red Crag Limestones will further expand our knowledge of the setting in the North Canterbury Region.

A full taxonomic study of the bryozoans seen at the Whiterock Limestone and comparison with the bryozoans observed in the Gowan Hill Sandstone and their relationship to the Whiterock Limestone, may help resolve age and environment differences if they exist.

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Appendix 1

Microfossil Preparation

Equipment, including wet sieves, brushes, pots and crushing surfaces were rinsed in 'methylene blue' after washing. This procedure stains carbonates a blue colour. Contamination was at a minimum, no foraminifera were stained, aside from fine to silt grains were present. These had probably been released from the wet sieve. Samples that were more cemented were crushed or hammered into 1 – 2cm^2 pieces.

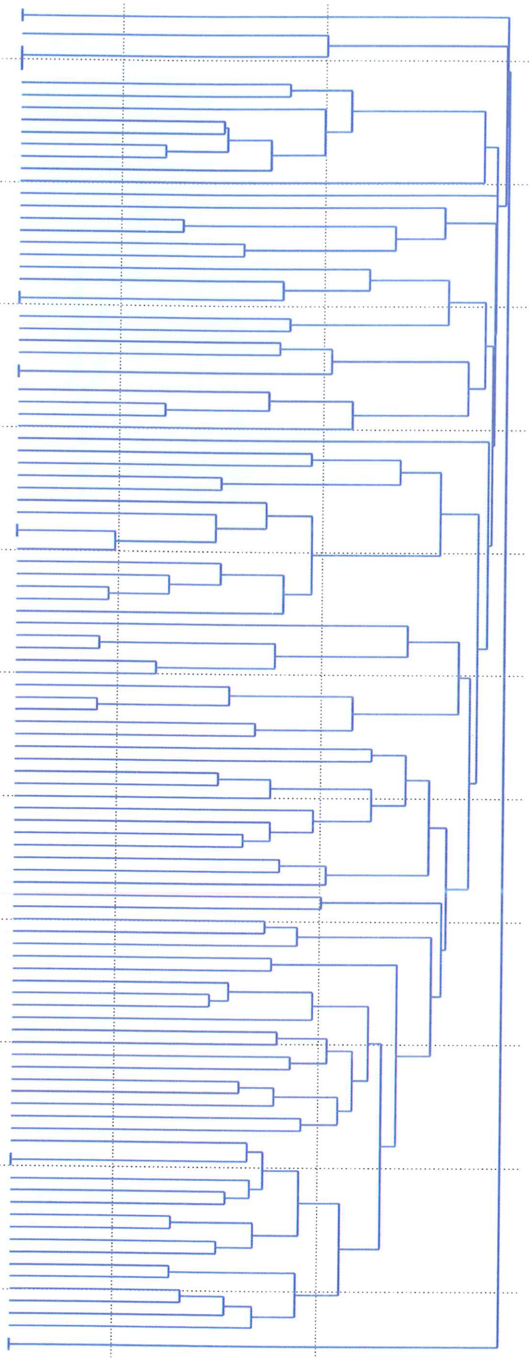
Procedure: Samples of fist size were crushed and oven dried at 50°C. . Following drying in the oven, samples were soaked in 20 vol H_2O_2 (approximately 5%) for 30 – 60 minutes. The sediment slurry was wet sieved to retain sediment of grain sizes larger than 0.071mm. The cleaned sediment was oven dried, labelled and sorted into bags. The samples are in the process of being recorded in the University of Canterbury Foraminifera record book and the Fossil Record File.

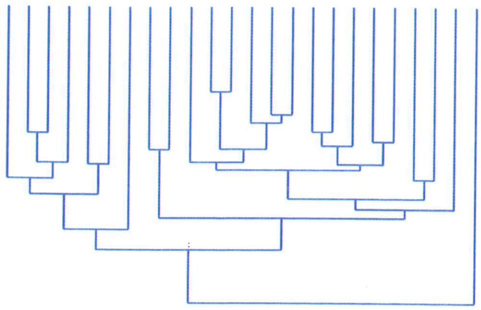
Macrofossil Preparation

Macrofossil preparation was undertaken to improve identification and to reduce the bulk rock mass. Methods involved included dental picks and scrapers. Excess bulk rock was removed and macrofossils were soaked in 20 vol H_2O_2 (approximately 5%) for 30 – 60 minutes. Macrofossils identified are currently being put into the Fossil Record File.

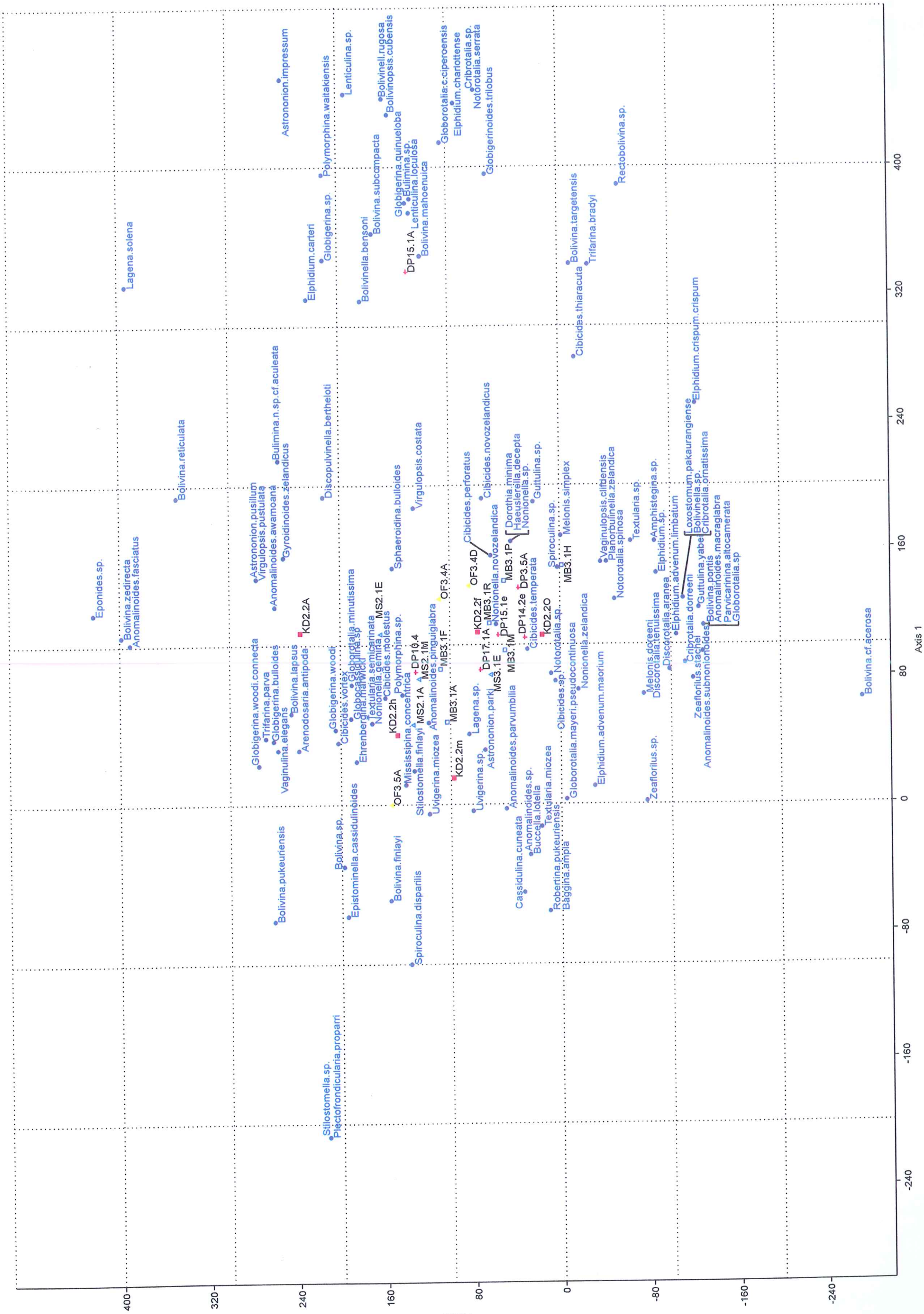
Appendix 3:
Bray Curtis Two-way Cluster Analysis: All Species Data

0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	Nonionella.gemina
0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	Textularia.semicarinata
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.3	0	0	0	0	0	Anomalinoides.macraglabra
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	Parvicarinina.altocamerata
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	Globorotalia.sp
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	Bolivina.pontis
0	0	0	0	0	0	0	0.4	2.2	0.3	0	0	0.3	0	0	2.7	0	0	0	0	0	0	0	0	Guttulina.yabei
0	0	0	0.3	0	0	0	0	1.1	0	0	0	0	0	0	0.7	0	0	0	0	0	0	0	0	Elphidium.advenum.limbatum
0	0	0	0	2.3	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	Spiroculina.disparilis
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.7	0	0	0	0	0	0	0	0	Vaginulopsis.clifdensis
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.7	0	0	0	0	0	0	0	0	Planorbulinella.zelandica
0	0	0	0	0	0	0	0.4	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	Guttulina.sp.
0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	1	0	0	0	0	0	0	0	0	Melonis.simplex
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1.3	0	0	0	0	Nonionella.zelandica
0	0	0	0	0	0	0	0	0.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Bolivina.cf.acerosa
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.7	0	0	Zeaflorilus.sp.
0	0	0	2.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Astrononion.pusillum
0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Virgulopsis.pustulata
0	0	0.3	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Vaginulina.elegans
0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Epistominella.cassidulinoides
0	0	1.4	0.3	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0.7	0	0	0	Mississipina.concentrica
0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0.7	0	0	0.7	0	0.7	0	0	0	0	Notorotalia.sp.
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	Nonionella.sp.
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0	Haeuslerella.decepta
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0	Dorothia.minima
0	0	0	0	0	0	0	2.1	0	0	0	0	0	0	1.4	0	0	0	0	0	0	0	0	0	Textularia.sp.
0	0	0	0	0	0	0	1.7	0.7	0	0	0	0	0	0	0	0	0.7	0	0	1	0	0	0	Amphistegina.sp.
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	Cribrotalia.ornatissima
0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.7	0	0	0	Melonis.doreeni
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	Loxostomum.pakaurangiense
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	Bolivinella.sp.
0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Baggina.ampla
0.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Robertina.pukeuriensis
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0	Textularia.miozea
0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0.3	0	0.3	Bolivina.targetensis
0	0	0	0	0	0.7	0	0	0	0	0	0.7	0	0.3	0	0	0	0	0	0	0	0	0	0	Uvigerina.miozea
0	0	0	0	0	0	0	0	0	0.3	0	0	0.3	0	0	0.3	0	0	0	0	0	0	0	0	Spiroculina.sp.
0	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	Rectobolivina.sp.
0	0	0	0	0	0	0	0	0	0	0	0.7	0	0	0	0	0	0	0	0	0	0	0	0.7	Polymorphina.waitakiensis
0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	Bulimina.n.sp.cf.aculeata
0	0	0	0	0	0	0	0	0	0	0	0	0	3.9	0	0	0	0	0.3	0	0	0	0	2.7	Globigerina.quinqueloba
0	0	0.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	3	Globigerinoides.trilobus
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.7	0	0	0	0	4	Cribrotalia.sp.
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.7	0	0	0	0	4	Notorotalia.serrata
0	0	0	0	0	0	0.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3.4	Astrononion.impressum
0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	1.7	Globorotalia.c.ciperoensis
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	1	Bolivinopsis.cubensis
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	1.3	Elphidium.charlottense
0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	1.3	Bolivinell.rugosa
0	0.7	0	0	0	0	0	0	0	0	1.3	0	0	0	0	0	0.3	0	0	0	0	0	0	2	Bulimina.sp.
0	0	0	0	0	0	0.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Eponides.sp.
0	0	0	0	0	0	3.4	0	0	0	0	0	0	0	0	0	0	0	0	0.7	0	0	0	0	Anomalinoides.fasciatus
0	0	0	0	0	0	3.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.7	Lagena.solena
0	0	0.7	0	0	0	8.6	0	0	0.3	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0	Bolivina.zedirecta
0	0	0.3	0.7	0	0	7.9	0	0	0	0	0.3	0	0.3	0	0	0	0.7	0	1	0.3	0	1.7	0.7	Bolivina.reticulata
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.3	0	Arenodosaria.antipoda
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0.7	0	Ehrenbergina.marwicki
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.7	0	0	0.7	0	Stilostomella.finlayi
0	0	0	0	0	0	0.4	0	0	0.3	1	0	0	0	0	0	0.7	0	0.3	0.7	0.7	0.3	0.3	0	Polymorphina.sp.
0	0.3	0	0	0	0	0.4	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0.7	1.3	0	Cibicides.vortex
0	0	1	1	1	0.3	0	0	0.4	0	0	0	0	0	1.4	0	0	0	0	0	0	1.3	0.3	0	Uvigerina.sp.
0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0.3	2.7	0	0	0.7	0	0	Cribrotalia.dorreeni
0	0	0	0	0	0.3	0	0	0	3.1	0	0	0	0	0	2.7	0	0	0	0	6	2.4	0	0	Zeaflorilus.stachei
0	0	0	0	0	0	0	0	0	3.4	0	0	0.3	1	0	0	0	0	0.3	0	1.3	2.4	0	0	Discorotalia.aranea
0	0	0.3	0	0	0	0	0	0	3.1	0	0.7	0	0.3	0.3	0	0	0	0	0.3	0.7	0	0.3	0	Discorotalia.tenuissima
0	0	0	5.7	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1.7	1	0	1.7	Elphidium.carteri
0	0	0	3	0	0	0	0	0	0	0	0	1	0	3.1	0	0	0	0	0.7	3.7	0.7	0	0	Nonionella.novozelandica
0	0	0	0	0	0	0.7	0	0	0	0	0	0	0.3	0	0	0	0	0	1	3.4	0.7	0	0.3	Virgulopsis.costata
0	1.7	1.4	1.4	0.3	0	1.5	0	0	0.3	0	1	0	0.7	0	0	0	0	0.3	0	3.4	0.7	0	0	Bolivina.lapsus
0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0.3	0.3	0	0	Notorotalia.spinosa
0	0	0	0	0	0	0	0	1.1	2.1	0.3	0	0	0.7	0	0	0.3	0.3	0	0	0	0	0	0	Anomalinoides.subnonionoides
0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0.3	0	0	0	0	0	0.7	Lenticulina.loculosa
2	2	1	0	0	0	0	0	1.1	0	0	0	0	0	0	0	3	0	0	2	0	0	0	0	Globorotalia.mayeri.pseudocontinuosa
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	1	0	0	0	0	0	1	Trifarina.bradyi
0	0	0	0	0	0	0	19	16.4	11	0	0	0	0	3.4	4.3	0	5.4	0	0	0.3	0	0	4.4	Elphidium.crispum.crispum
0.3	0.3	0	0	0.3	0	0	16.9	5.6	0	0.7	0	0.3	1.3	1.7	0	1.7	0	3.4	0	1.3	2.4	0	0	Elphidium.sp.
0	0	0	0	0	0	0	11.2	0	0	0	0	0	0	0	9.3	1.4	13.6	1	0	0	1.3	0	3	Cibicides.thiaracuta
1	2.4	0	0	0	7.3	0	0	0	0	0	2	0	0	0	0	0	0	0	7.2	0	0	0	0	Cassidulina.cuneata
2	2	0	2.7	0	6.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	6.4	Bolivina.mahoenuica
0	0	1.7	3.7	1	0.7	0	0	0	0.3	1	2.9	5.4	0.7	0.3	0.3	0.3	0	0	0	4	0	0	10.1	Bolivina.subcompacta
1	1.4	0	1.4	1	0.7	1.9	1.7	0.4	1.7	1.3	2.6	0.3	1	0.7	1.7	0.3	0	0	0	0.3	0	1	6.4	Globigerina.sp.
0.7	1	3.7	4.7	0.7	0.3	0.7	0	1.9	1.4	1.3	2.3	3.4	1.6	1.4	0	0	0.7	0.7	2	0	0.7	2.7	6.7	Bolivinella.bensoni
0	0	0	0	0	0	0.7	0.8	0	0	0.3	0	0.7	0	0	0	0	0	0	0	0	0	0.3	14.1	Lenticulina.sp.
1	0.7	0	0	2	0	0.4	0	1.5	0	0	0	1.7	2	0.7	0	0.7	0.7	0	1	0.3	0	0	0	Anomalinoides.pinguiglabra
2.3	0.7	0	0	0.7	0	0	0.4	0.7	0.3	0.7	0	1.3	0.7	0	0.3	0	0	1	0.3	0.3	0	2.3	0	Lagena.sp.
0	0.3	0	1.4	1	2.6	2.6	0	1.5	1.4	0	0	1	0.3	0	0	0.3	1	0	1	0	0	2	0	Globigerina.bulloides
0	0.3	1.7	0.7	5.7	1	0.7	0	0.7	1	0	1.3	0	0	0	1	0.7	0	0	0	0.3	0.3	3.7	0	Bolivina.sp.
3.6	2.4	1.7	2.4	0.3	0.3	1.1	0	0	0	0.7	1	0.3	1.3	0	0.3	0.3	1.7	2	0	0	0	0.3	1.7	Discopulvinella.bertheloti
4.6	2.7	0	0	0	0	3.4	0	0.7	1	0	0.7	0.3	0	0.7	0	1.4	2	0	0	1.7	0	1.7	1.3	Gyroidinoides.zelandicus
0	3.4	1	0.7	0	0.7	1.5	2.1	1.1	1.4	2.6	0.7	0	2.3	1	0	0.7	1.7	0	0	0	0	0	0	Globorotalia.minutissima
0	1	0	0	0	0	2.6	0	4.5	1.7	0.7	0	3.7	0	1.4	0	0	3.1	0	1.3	2	3	0	0.7	Sphaeroidina.bulloides
2.3	2	2.4	0	0	0	1.5	0	0.4	0	4	0.3	3.7	0	1.4	0	0	0.7	2.3	6.6	0	6.1	10.1	0.7	Cibicides.molestus
6.9	4.4	2.4	3	2	2	0.7	0	0.4	2.1	3.3	3.3	0	2.6	2.4	5.3	2.4	0	3	0	3	2.4	0	0	Astrononion.parki
7.2	1.7	5.1	1.7	11	7.9	0	2.1	1.5	5.1	2.3	3.3	1.3	0	0	0	0	0	0.7	1	3.4	12.1	0	0	Anomalinoides.sp.
7.2	1.7	5.1	1.7	11	7.9	0	2.1	1.5	5.1	2.3	3.3	1.3	0	0	0	0	0	0.7	1	3.4	12.1	0	0	Buccella.lotella
11.5	1	1.4	5.7	1.3	13.5	0	0.8	0.7	2.7	3.3	1	0	0	3.1	0	1	1.7	0	0.7	5	0	5.4	0	Anomalinoides.parvumbilia
5.9	9.8	10.5	0.7	1.3	13.9	0	5	17.5	3.8	3.6	3.3	0	0	2	0	5.1	3.1	0	1.3	9.1	1.7	0	0	Elphidium.advenum.maorium
3.9	13.6	10.9	8.8	27.8	19.8	1.9	1.7	4.1	3.1	0.7	3.6	0	1	0.7	0	1.7	0.7	0.7	1.6	1.7	1.3	7.4	0	Bolivina.finlayi
2.3	4.1	2.4	5.4	5	3	7.5	0	0.4	0	6.6	4.9	4.7	0	0	0	0	0	2.3	0	0	1	0.7	0	Globigerina.woodi.connecta
3	1	6.5	8.1	4.7	0.3	8.2	2.5	1.9	0.7	6.3	7.2	1.3	2	2.4	0	0	0	0.7	2.3	0.3	1	4.7	0	Trifarina.parva
0	5.4	6.5	4.4	10.7	3	6	0.4	0.4	0	0.3	1	2.7	0	3.1	0	0	0	0	0	0	5.7	0	4	Anomalinoides.awamoana
1.6	7.8	1.7	2.7	8.4	5.9	3.4	0	0	0	0	2.9	0	0	0	0	0	0	0	0	0	0	0	0	Bolivina.pukeuriensis
1	0.7	3.4	4.4	0	0	11.6	6.2	7.5	12.7	6.3	5.6	11.4	18.8	14	22	28.7	6.1	18.8	14.8	20.1	24.6	5.4	7.1	Cibicides.perforatus
10.5	3.7	5.1	7.8	1.3	4	3.4	13.2	10.1	18.2	23.8	19.9	24.8	24	25.9	30.7	25	31.6	34.6	24.6	7.7	18.5	11.7	0	Cibicides.temperata
8.2	5.1	0.3	4.7	2.7	3.3	4.9	1.2	0	1.7	8.9	9.2	3.7	2.3	2	2.7	5.4	3.4	2.3	4.6	2.7	1	8.7	0	Globigerina.woodi
9.2	13.6	18.7	6.4	4.3	0	7.5	5.8	3.4	3.4	7.9	9.8	9.4	8.2	9.6	4	6.1	4.4	5	0.7	4	1.3	5.4	0	Globocassidulina.sp
4.3	0.3	1	0.3	0.3	0	0	2.1	3	5.8	6	3.6	10.7	15.8	8.2	2.7	5.7	6.1	0.3	2	1.3	0	6.7	3.7	Cibicides.novozelandicus
1	1	0.3	1.4	1	0.3	0.4	1.7	6.3	3.1	2	2.6	3.7	2.3	2.4	3.3	3	4.8	13.8	15.1	2.7	2.4	9.4	0	Cibicides.sp.
0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Stilostomella.sp.
0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Plectofrondicularia.proparri
MB3.1A	KD2.2h	MS2.1A	MS2.1E	DP1.5A	KD2.2m	KD2.2A	MB3.1H	KD2.2O	DP14.2e	MB3.1F	MS2.1M	DP1.4A	DP1.4D	KD2.2l	DP3.5A	MB3.1R	MB3.1P	MB3.1M	DP17.1A	DP15.1e	MS3.1E	DP10.4	DP15.1A	



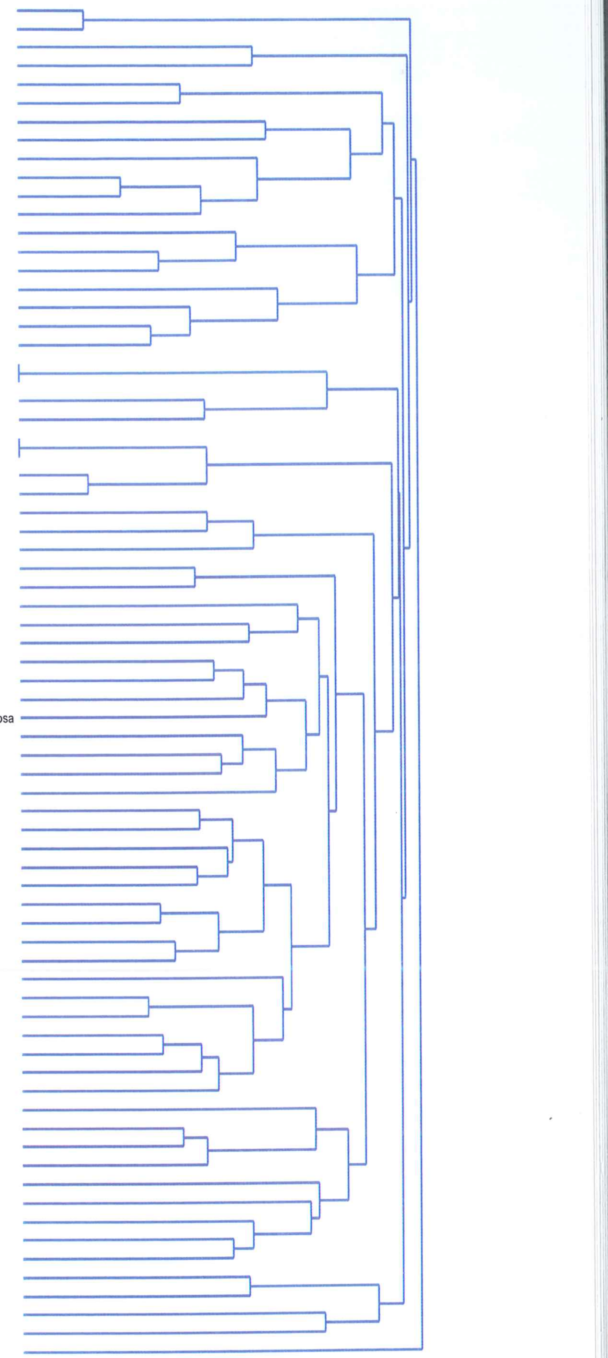


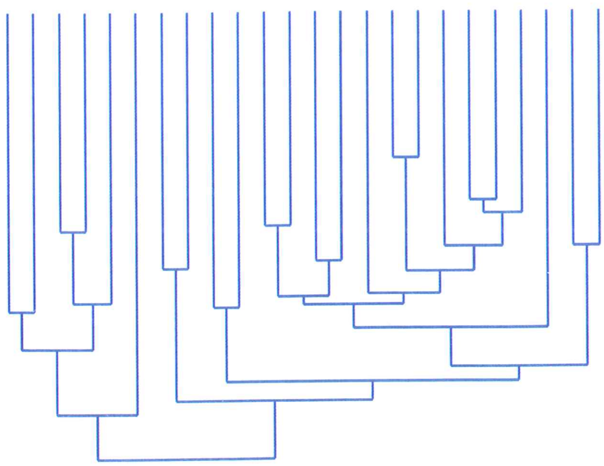
Appendix 3:
Detrended Correspondence Analysis: All Species Data



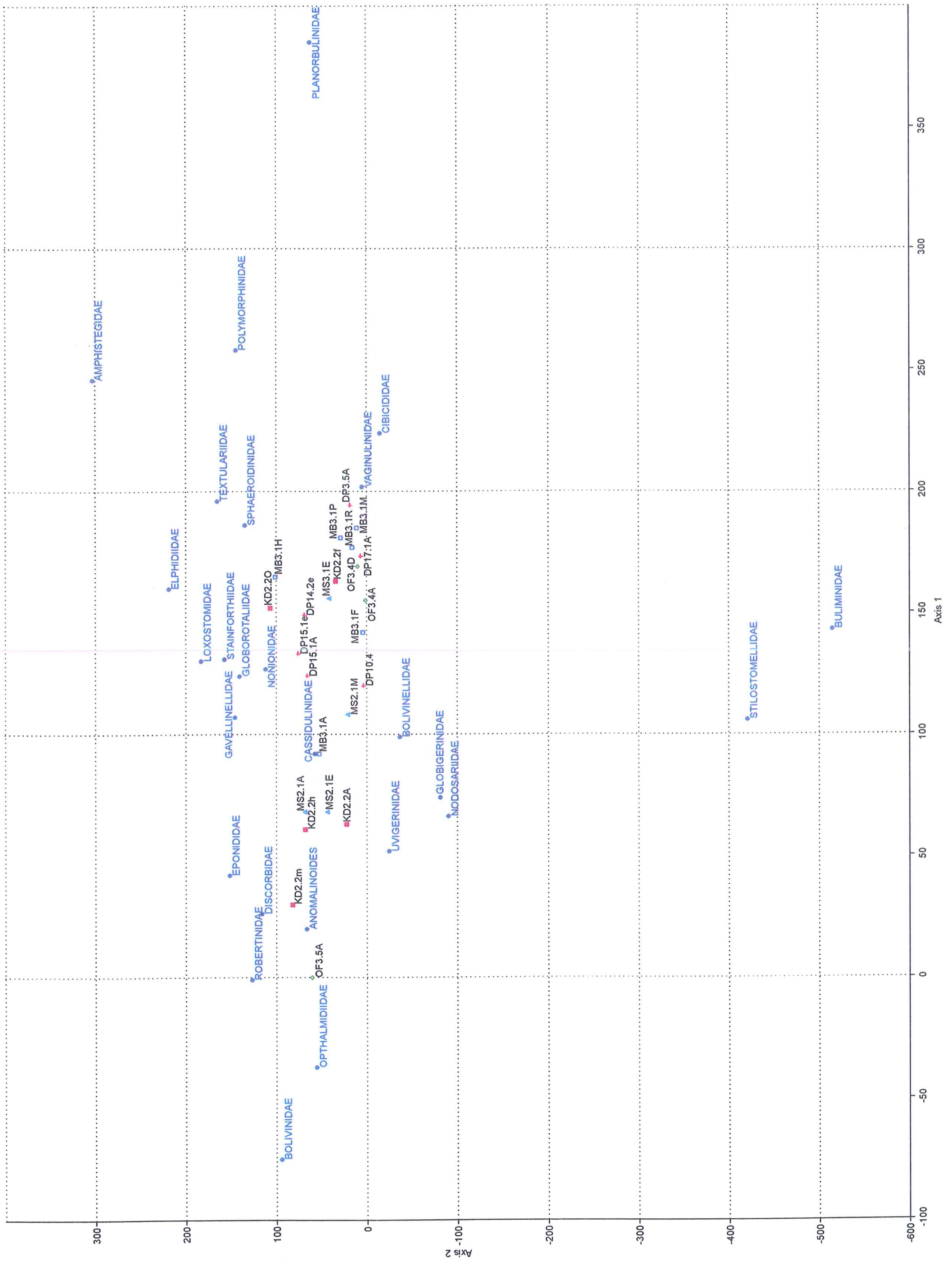
Appendix 3:
Bray Curtis Two-way Cluster Analysis: Rare Species Removed

OF3.5A	KD2.2m	KD2.2h	MS2.1A	MS2.1E	KD2.2A	MB3.1H	KD2.2O	MB3.1A	DP10.4	DP3.5A	MB3.1P	MB3.1M	DP17.1A	DP14.2e	MB3.1F	MS2.1M	MB3.1R	OF3.4A	KD2.2f	OF3.4D	MS3.1E	DP15.1A	DP15.1e	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	Polymorphina.sp.
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.4	0	0	0	0	0	0	0	0	Bulimina.sp.
0	0	0	0	0	0	0	0	0	0	0	1.1	0	0	0	0	0	0	0	0	0	0	0	0	Nonionella.sp.
0	0	0	0	0	0	0	0	0	0	0	1.1	0	0	0	0	0	3.2	0	0	0	0	0	0	Trifarina.bradyi
0	0	0	0	0	0	0	0	0	1.4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	Cibicides.vortex
0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	Arenodosaria.antipoda
0	0	0	0	0	0	0	2.4	0	0	2.8	0	0	0	0	0	0	0	0	0	0	0	0	0	Guttulina.yabei
0	0	0	0	0	0	0	1.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Elphidium.advenum.limbatum
2.4	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	Spiroculina.disparilis
0	0	0	0	0	0	0	0	0	0	1.7	0	0	0	0	0	0	0	0	0	0	0	0	0	Planorbulinella.zelandica
0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	Melonis.simplex
0	0	0	0	0	0	0	0	0	0	1	0	0	1.4	0	0	0	0	0	0	0	0	0	0	Nonionella.zelandica
0	0	0	0	0	0	0	0	0	0	0	0	0	0	3.6	0	0	0	0	0	1	2.5	0	1.4	Discorotalia.aranea
0	0	0	0	0	0	0	0	0	0	0	0	0	0	3.2	0	0	0	0	0	0	0	0	0	Discorotalia.tenuissima
0	0	0	0	0	0	0	1.2	0	0	0	0	0	0	2.1	0	0	0	0	0	0	0	0	0	Anomalinoides.subnonionoides
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.1	0	0	0	0	Globigerina.quinueloba
0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.1	0	0	0	0	0	1	0	0	0	Notorotalia.spinosa
0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	Guttulina.sp.
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	Lenticulina.loculosa
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.1	Globigerinoides.trilobus
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.1	Cribrotalia.ornatissima
0	0	0	0	0	0	2.2	0	0	0	0	0	0	0	0	0	0	0	0	1.4	0	0	0	0	Textularia.sp.
0	0	0	0	0	0	1.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.1	Amphistegina.sp.
0	0	0	0	0	3.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Anomalinoides.fasciatus
0	0	0	0	0	3.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Lagena.solena
0	0	0	0	0	9.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Bolivina.zedirecta
0	0	0	0	0	8.4	0	0	0	1.7	0	0	0	1	0	0	0	0	0	0	0	0	0	0	Bolivina.reticulata
0	0	0	0	0	0	19.8	17.6	0	0	4.5	5.9	0	0	11.4	0	0	0	0	3.6	0	0	1.4	0	Elphidium.crispum.crispum
0	0	0	0	0	0	17.7	6	0	0	0	0	3.6	0	0	0	0	1.8	0	1.8	1.4	2.5	1.8	1.4	Elphidium.sp.
0	0	0	0	0	0	11.6	0	0	0	9.7	14.7	1.1	0	0	0	0	1.4	0	0	0	1.4	0	0	Cibicides.thiaracuta
0	7.6	2.5	0	0	0.	0	0	1	0	0	0	0	7.7	0	0	2	0	0	0	0	0	0	0	Cassidulina.cuneata
0	7.3	2.1	0	2.9	0	0	0	2	2.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Bolivina.mahoenuica
2.1	0	0	0	0	0	0	1.6	1	0	0	0	0	1	0	0	0	0	1.7	0	2.1	0	0	0	Anomalinoides.pinguiglabra
1	2.8	0	0	1.4	2.8	0	1.6	0	2.1	0	1.1	0	1	1.4	0	0	0	1	0	0	0	0	0	Globigerina.bulloides
0	0	1.1	0	0	2.8	0	4.8	0	0	0	3.3	0	1.4	1.8	0	0	0	3.8	1.4	0	3.3	0	2.1	Sphaeroidina.bulloides
0	0	2.5	1.7	2.5	1.2	0	0	3.7	0	0	1.8	2.2	0	0	0	1	0	0	0	1.4	0	1.1	0	Discopulvinella.bertheloti
0	0	2.8	0	0	3.6	0	0	4.7	1.7	0	2.2	0	0	1.1	0	0	1.4	0	0	0	0	1.8	1.8	Gyroidinoides.zelandicus
0	0	3.5	1	0	1.6	2.2	1.2	0	0	0	1.8	0	0	1.4	2.8	0	0	0	1.1	2.4	0	1.4	0	Globorotalia.minutissima
0	0	2.1	1	0	0	0	1.2	2	0	0	0	0	2.1	0	0	0	3.2	0	0	0	0	1.8	0	Globorotalia.mayeri.pseudocontinuosa
1	0	1.4	0	1.4	2	1.7	0	1	1	1.7	0	0	0	1.8	1.4	2.7	0	0	0	1	0	0	0	Globigerina.sp.
1	1.4	1.4	4.2	0	0	0	0	0	1.4	1.4	1.1	0	1.7	0	1.7	1.4	0	0	0	1	0	0	0	Anomalinoides.sp.
0	0	1.1	3.8	5	0	0	2	0	2.8	0	0	0	2.1	1.4	1.4	2.4	0	3.5	1.4	1.7	0	1.4	0	Bolivinella.bensoni
5.9	1	0	1.7	0	0	0	0	0	3.8	1	0	0	0	1.1	0	1.4	0	0	0	0	0	2.1	0	Bolivina.sp.
2.1	2.1	4.6	2.4	3.2	0	0	0	7.1	0	5.5	0	3.2	0	2.1	3.5	3.4	2.5	0	2.5	2.8	2.5	3.5	3.2	Astrononion.parki
1.4	14.2	1.1	1.4	6.1	0	0	0	11.8	5.6	0	1.8	0	0	2.9	3.5	1	1.1	0	3.2	0	0	4.3	5	Anomalinoides.parvumbilia
11.4	8.3	1.8	5.2	1.8	0	2.2	1.6	7.4	0	0	0	0	1	5.4	2.4	3.4	0	1.4	0	0	13	0	3.6	Buccella.lotella
1.4	14.5	10.3	10.8	0	0	5.2	18.8	6.1	0	0	3.3	0	1.4	3.9	3.8	3.4	5.4	0	2.2	0	1.8	4.6	9.6	Elphidium.advenum.maorium
28.7	20.8	14.2	11.2	9.3	2	1.7	4.4	4.1	7.7	0	0	0	1.7	3.2	0	3.7	1.8	0	0	1	1.4	7.1	1.8	Bolivina.finlayi
5.2	3.1	4.3	2.4	5.7	8	0	0	2.4	0	0	0	2.5	0	0	7	5.1	0	4.9	0	0	1.1	3.2	0	Globigerina.woodi.connecta
4.8	0	1.1	6.6	8.6	8.8	2.6	2	3	4.9	0	0	0	2.4	0	6.6	7.5	0	1.4	2.5	2.1	1.1	1.1	0	Trifarina.parva
11.1	3.1	5.7	6.6	4.7	6.4	0	0	0	0	0	0	0	0	0	0	1	0	2.8	3.2	0	6.2	0	0	Anomalinoides.awamoana
8.7	6.2	8.2	1.7	2.9	3.6	0	0	1.7	0	0	0	0	0	0	0	3.1	0	0	0	0	0	0	0	Bolivina.pukeuriensis
0	0	2.1	2.4	0	1.6	0	0	2.4	10.5	0	0	2.5	7	0	4.2	0	0	3.8	1.4	0	6.5	3.2	0	Cibicides.molestus
0	0	0	3.5	4.7	12.4	6.5	8	1	5.6	22.8	6.6	20.1	15.7	13.2	6.6	5.8	30.4	11.9	14.7	19.7	26.4	14.9	21.4	Cibicides.perforatus
1.4	4.2	3.9	5.2	8.2	3.6	13.8	10.8	10.8	12.2	31.7	34.1	36.9	26.1	18.9	25.2	20.7	26.4	25.9	27.3	25.2	19.9	7.4	8.2	Cibicides.temperata
2.8	3.5	5.3	0	5	5.2	1.3	0	8.4	9.1	2.8	3.7	2.5	4.9	1.8	9.4	9.5	5.7	3.8	2.2	2.4	1.1	2.8	2.9	Globigerina.woodi
4.5	0	14.2	19.2	6.8	8	6	3.6	9.5	5.6	4.1	4.8	5.4	0	3.6	8.4	10.2	6.4	9.8	10.1	8.6	1.4	6.7	4.3	Globocassidulina.sp
0	0	0	1	0	0	2.2	3.2	4.4	7	2.8	6.6	0	2.1	6.1	6.3	3.7	6.1	11.2	8.6	16.6	0	0	1.4	Cibicides.novozelandicus
1	0	1.1	0	1.4	0	1.7	6.8	1	9.8	3.4	5.1	14.7	16	3.2	2.1	2.7	3.2	3.8	2.5	2.4	2.5	3.9	2.9	Cibicides.sp.
0	0	0	1.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.8	0	Mississipina.concentrica
0	0	0	0	0	0	0	0	0	0	0	0	0	0	3.2	0	0	0	0	2.9	0	2.5	6.7	6.4	Zeaflorilus.stachei
0	0	0	0	3.2	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3.2	0	0	4.3	3.9	Nonionella.novozelandica
0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	10.6	3.6	Virgulopsis.costata
1	0	0	1	1.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.4	0	1.4	0	0	Uvigerina.sp.
0	0	0	0	2.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Astrononion.pusillum
0	0	0	0	6.1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1.1	0	1.8	Elphidium.carteri
1	0	0	1.7	3.9	0	0	0	0	0	0	0	0	0	0	1	3.1	0	5.6	0	0	0	0	4.3	Bolivina.subcompacta
0	0	1.8	1.4	1.4	1.6	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	3.6	Bolivina.lapsus
0	0	0	0	0	0	0	0	0	0	0	0	2.9	0	1.1	0	0	0	0	1.1	0	0	0	0	Cribrotalia.dorreeni
0	0	0	0	0	0	0	0	0	0	0	0	1.4	0	0	0	0	0	0	0	0	0	0	0	Anomalinoides.macraglabra
0	0	0	0	0	0	0	0	2.4	2.4	0	0	1.1	0	0	0	0	0	1.4	0	0	0	0	0	Lagena.sp.
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	Bulimina.n.sp.cf.aculeata
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Bolivinell.rugosa

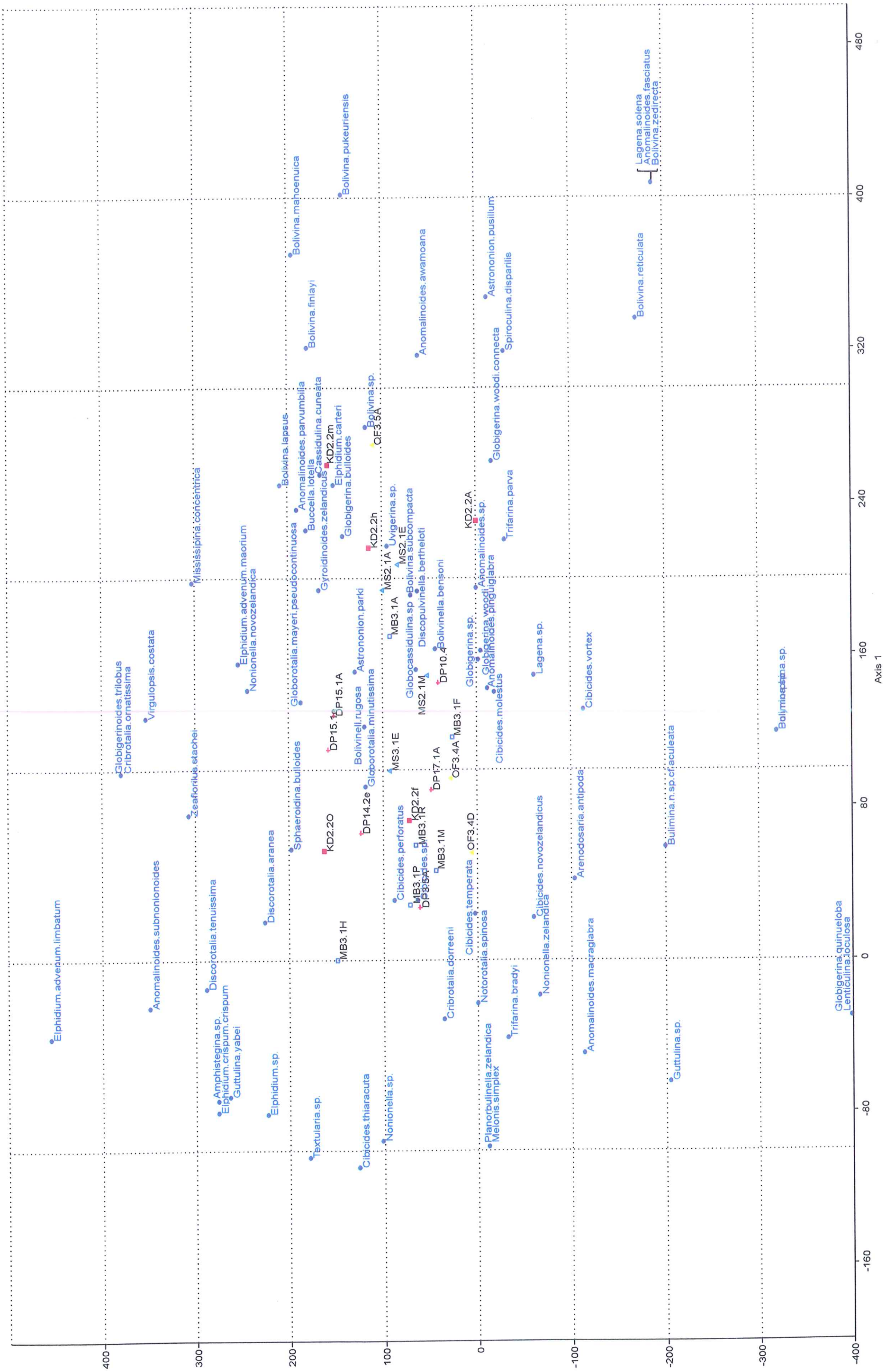




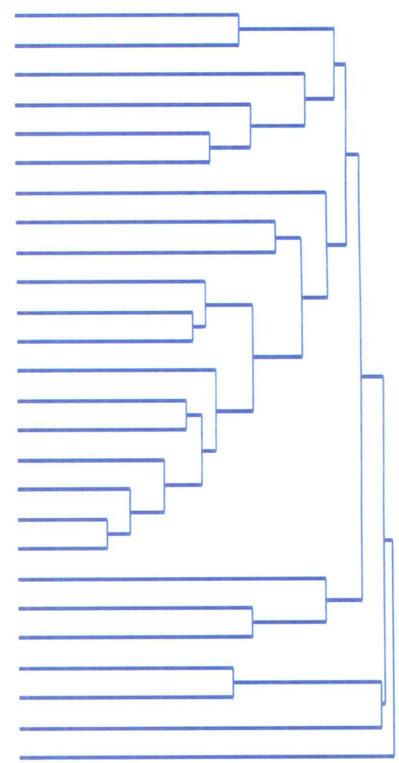
Appendix 3:
Detrended Correspondence Analysis: All Families of Foraminifera



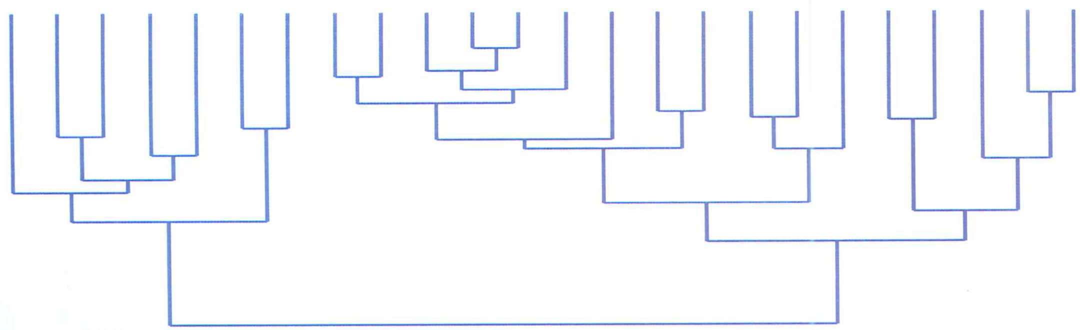
Appendix 3:
Detrended Correspondence Analysis: Rare Species Removed



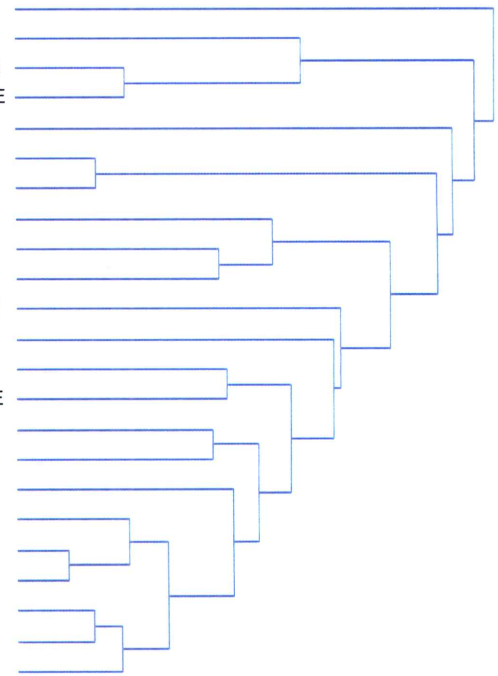
Appendix 3:
Bray Curtis Two-way Cluster Analysis: All Foraminifera Families



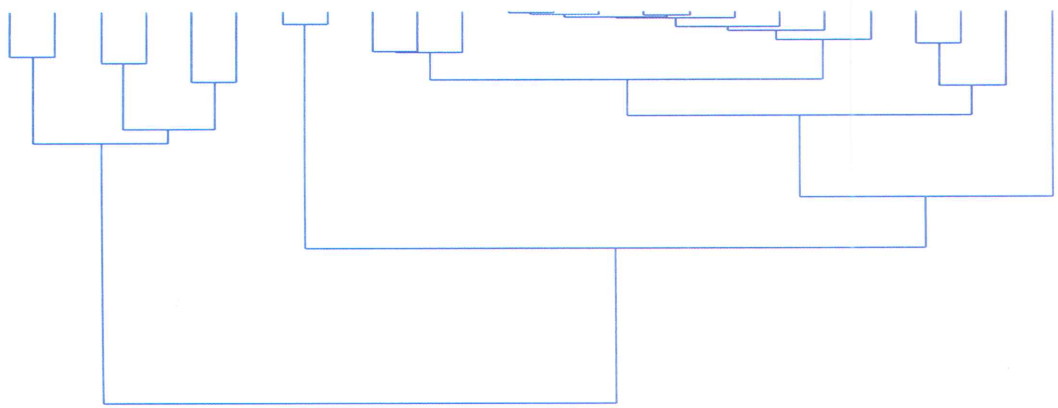
	MB3.1A	KD2.2A	MS2.1E	KD2.2h	MS2.1A	OF3.5A	KD2.2m	DP3.5A	MB3.1M	MB3.1R	OF3.4D	DP17.1A	MB3.1P	OF3.4A	KD2.2f	MS3.1E	MB3.1F	MS2.1M	DP10.4	DP15.1A	DP15.1e	DP14.2e	MB3.1H	KD2.2O
TEXTULARIIDAE	1	0	0	0	0	0	0	0	0	0	0	0	1	0	1.4	0	0.3	0	1.7	0	0	0	2.1	0
AMPHISTEGIDAE	0	0	0	0	0	0	0	0	0	0	0	0	0.7	0	0	0	0	0	0	0	1	0	1.7	0.7
BULIMINIDAE	0	0	0	0.7	0	0	0	0	0	0.3	0	0	0	1	0	0	1.3	0	0	0	0	0	0	0
NODOSARIIDAE	2.3	3.5	0.3	0.7	0.3	1	0	0.3	1	0	0.7	0.3	0	1.3	0	0	0.7	0	2.3	0.7	0.3	0.3	0.4	0.7
POLYMORPHINIDAE	0	0.4	0	0	0	0	0	3.7	0.3	0.7	1	0.7	0	1	0	0.3	1	0	0.3	0.7	0.7	0.7	0.8	2.2
VAGINULINIDAE	0	0.7	0	0	0	0	0	0.7	0	0	1	0	0.3	0.7	0	0	0.3	0	0.3	0.7	0	0	0.8	0
CIBICIDIDAE	19.1	17.8	13.9	8.1	12.2	2.7	4.3	68	70.8	64.2	60.9	63.9	62.9	54.5	51.9	53.5	42.1	32.2	44.6	28.6	31.9	39.7	34.3	27.2
GAVELLINELLIDAE	4.6	0	0	2.7	0	0	0	0	0	1.4	0	0	2	0	0.7	0	0	0.7	1.7	1.7	1.7	1	0	0.7
SPHAEROIDINIDAE	0	2.7	0	1	0	0	0	0	0	0	0	1.3	3.1	3.7	1.4	3	0.7	0	0	0	2	2.1	0	4.5
GLOBOROTALIIDAE	2	1.6	1	5.4	2	0	0.7	0	0.3	4.1	2.3	2	1.7	0	1	0.3	2.6	0.7	0	3	0	1.4	2.1	2.2
BOLIVINELLIDAE	0.7	0.7	4.7	1	3.7	0.7	0.3	0	0.7	0	1.6	2	0.7	3.7	1.4	0.7	1.3	2.3	2.7	2	0.3	1.4	0	1.9
UVIGERINIDAE	3	8.5	9.1	1	7.5	5.7	1.3	0	0.7	3	2.3	2.3	1	1.3	3.8	2.4	6.3	7.2	5	1	0.3	0.7	2.5	2.2
ELPHIDIIDAE	6.3	0	6.8	10.2	10.9	1.7	13.9	5.7	7	6.8	3.6	2.6	9.5	0.7	9.2	8.4	4.6	4.9	0.3	7.4	16.8	23.3	40.9	40.7
DISCORBIDAE	11.2	1.2	4.1	4.1	7.8	11.4	8.3	0.3	3	0.3	1.3	1	1.7	1.7	0	12.1	3	4.3	0.3	1	3.4	5.1	2.1	1.5
NONIONIDAE	7.2	1.2	8.4	4.4	2.4	2	2.3	7.3	3	2.4	3	2	1	1	8.2	6.1	3.6	3.3	0	13.8	13.4	5.1	0	0.4
BOLIVINIDAE	7.9	24.8	20.6	25.4	18.4	43.1	34.3	1.3	1.3	2.7	2.6	2.6	1.7	5.4	1.4	2.7	1.7	12.2	14.8	9.8	9.7	5.1	1.7	5.2
ANOMALINOIDES	12.5	10.1	10.5	8.5	11.9	15.1	17.8	1.3	1.7	2	3.6	3.9	3.7	4.4	7.5	6.4	5.6	3.3	6.7	4	5	5.5	2.1	3.7
GLOBIGERINIDAE	11.5	17.4	13.5	10.8	2.7	9.7	9.6	4.3	5	6.1	7.6	5.6	4.4	9.8	2.7	2	16.9	16.8	12.4	5.7	5	4.8	2.9	2.6
CASSIDULINIDAE	10.2	7.8	6.4	15.9	18.7	4.3	7.3	4	5	6.1	8.2	8.2	4.4	9.4	9.6	1.3	7.9	11.8	6	6.4	4	3.4	5.8	3.4
LOXOSTOMIDAE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.7	0.3	0	0	0
EPONIDIDAE	0	0.8	0.3	0	1.4	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	2.7	0.7	0	0	0
STAINFORTHIIDAE	0	0.7	0.3	0	0	0	0	0	0	0	0.3	1	0	0	0	0.7	0	0	0	10.1	3.4	0	0	0
PLANORBULINIDAE	0	0	0	0	0	0	0	1.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OPTHALMIDIIDAE	0	0	0	0	0	2.3	0	1.3	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0.3	0	0
STILOSTOMELLIDAE	0	0	0	0	0	0.3	0	0	0	0	0	0.7	0	0	0	0	0	0	0.7	0	0	0	0	0
ROBERTINIDAE	0.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0



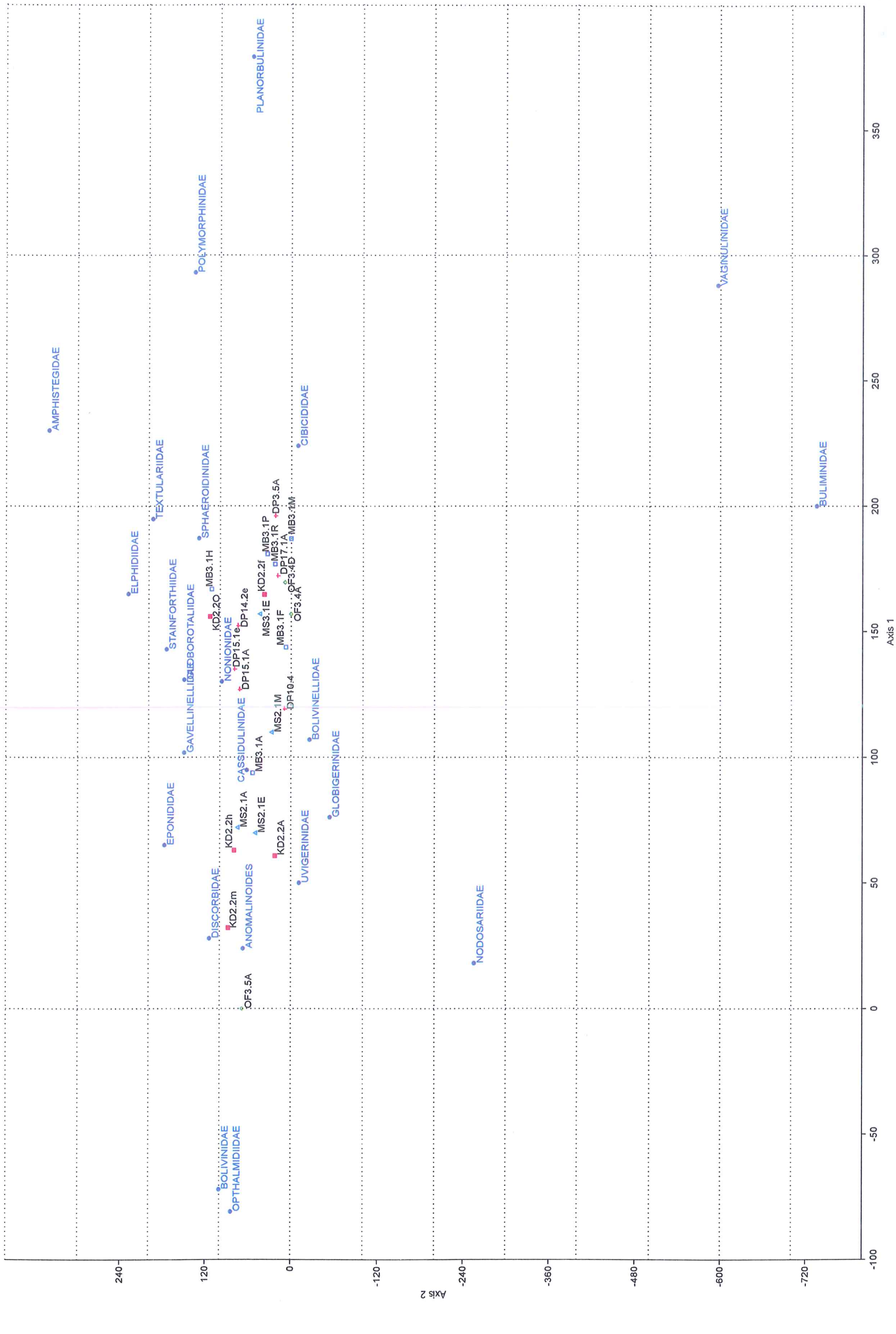
Appendix 3:
Bray Curtis Two-way Cluster Analysis: Foraminifera Families <1% Removed



Family	OF3.5A	KD2.2m	KD2.2A	MS2.1E	KD2.2h	MS2.1A	MB3.1H	KD2.2O	MB3.1F	MS2.1M	DP10.4	DP17.1A	OF3.4D	MB3.1R	MB3.1M	MB3.1P	DP3.5A	OF3.4A	KD2.2f	MS3.1E	DP14.2e	DP15.1e	DP15.1A	MB3.1A
VAGINULINIDAE	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
OPTHALMIDIIDAE	2.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.4	0	0	0	0	0	0	0
PLANORBULINIDAE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.7	0	0	0	0	0	0	0
POLYMORPHINIDAE	0	0	0	0	0	0	0	2.3	1	0	0	0	1	0	0	0	3.7	1	0	0	0	0	0	0
BULIMINIDAE	0	0	0	0	0	0	0	0	1.4	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
EPONIDIDAE	0	0	0	0	0	1.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.8	0
STAINFORTHIIDAE	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	3.4	10.4	0
TEXTULARIIDAE	0	0	0	0	0	0	2.1	0	0	0	1.7	0	0	0	0	1	0	0	1.4	0	0	0	0	1
AMPHISTEGIDAE	0	0	0	0	0	0	1.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
ELPHIDIIDAE	1.7	14	0	6.8	10.3	10.9	41.8	41.8	4.7	5	0	2.7	3.7	6.8	7.2	9.7	5.7	0	9.3	8.6	23.8	17.2	7.6	6.3
SPHAEROIDINIDAE	0	0	2.8	0	1	0	0	4.6	0	0	0	1.3	0	0	0	3.1	0	3.8	1.4	3.1	2.1	2.1	0	0
NODOSARIIDAE	1	0	3.6	0	0	0	0	0	0	0	2.4	0	0	0	1	0	0	1.4	0	0	0	0	0	2.3
GAVELLINELLIDAE	0	0	0	0	2.7	0	0	0	0	0	1.7	0	0	1.4	0	2.1	0	0	0	0	1	1.7	1.7	4.7
GLOBOROTALIIDAE	0	0	1.7	1	5.5	2	2.1	2.3	2.7	0	0	2	2.3	4.1	0	1.7	0	0	1	0	1.4	0	3.1	2
CIBICIDIDAE	2.7	4.2	18.5	14	8.2	12.3	35	28	42.9	32.8	45.5	65	61.5	65.1	72.3	64	68.9	55.5	52.2	54.6	40.6	32.8	29.4	19.3
NONIONIDAE	2	2.3	1.2	8.5	4.5	2.4	0	0	3.7	3.3	0	2	3	2.4	3.1	1	7.4	1	8.2	6.2	5.2	13.8	14.2	7.3
BOLIVINELLIDAE	0	0	0	4.8	1	3.8	0	1.9	1.4	2.3	2.7	2	1.7	0	0	0	0	3.8	1.4	0	1.4	0	2.1	0
DISCORBIDAE	11.5	8.3	1.2	4.1	4.1	7.8	2.1	1.5	3	4.3	0	1	1.3	0	3.1	1.7	0	1.7	0	12.4	5.2	3.4	1	11.3
ANOMALINOIDES	15.2	18	10.4	10.6	8.6	11.9	2.1	3.8	5.7	3.3	6.8	4	3.7	2.1	1.7	3.8	1.4	4.5	7.6	6.5	5.6	5.2	4.2	12.7
BOLIVINIDAE	43.6	34.7	25.7	20.8	25.8	18.4	1.7	5.4	1.7	12.4	15.1	2.7	2.7	2.7	1.4	1.7	1.4	5.5	1.4	2.7	5.2	10	10	8
GLOBIGERINIDAE	9.8	9.7	18.1	13.7	11	2.7	2.9	2.7	17.2	17.1	12.7	5.7	7.6	6.2	5.1	4.5	4.4	9.9	2.7	2.1	4.9	5.2	5.9	11.7
UVIGERINIDAE	5.7	1.3	8.8	9.2	1	7.5	2.5	2.3	6.4	7.4	5.1	2.3	2.3	3.1	0	1	0	1.4	3.8	2.4	0	0	1	3
CASSIDULINIDAE	4.4	7.3	8	6.5	16.2	18.8	5.9	3.4	8.1	12	6.2	8.3	8.3	6.2	5.1	4.5	4.1	9.6	9.6	1.4	3.5	4.1	6.6	10.3

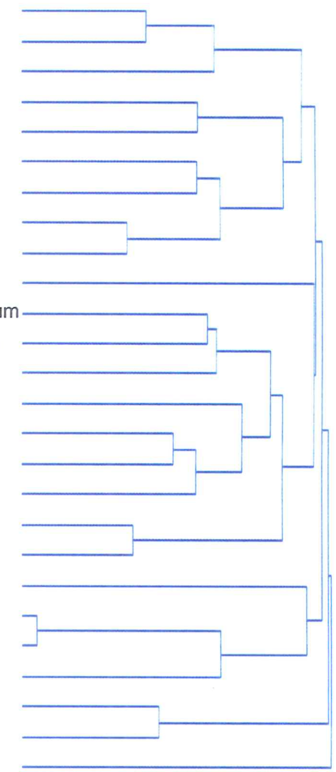


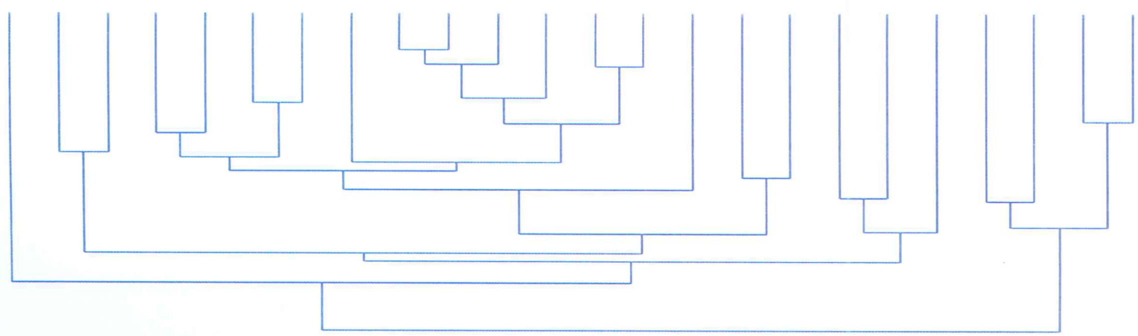
Appendix 3:
Detrended Correspondence Analysis: Families of <1% Removed



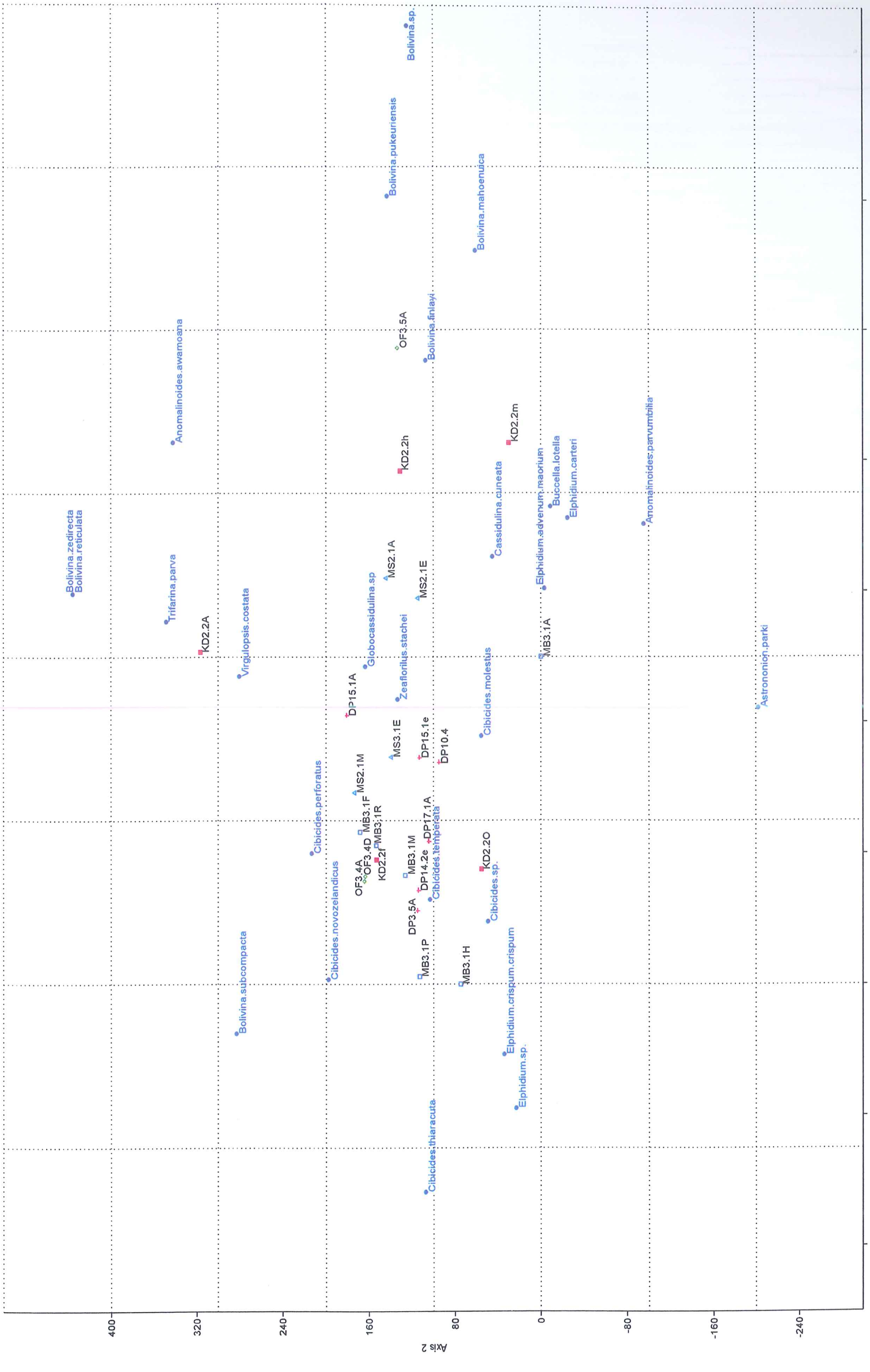
Appendix 3:
Bray Curtis Two-way Cluster Analysis: Species >5%

Species	KD2.2A	KD2.2O	MB3.1H	MB3.1P	DP3.5A	MB3.1M	DP17.1A	DP14.2e	OF3.4A	KD2.2f	OF3.4D	MB3.1R	MS2.1M	MB3.1F	MS3.1E	DP15.1e	DP15.1A	DP10.4	MS2.1E	MB3.1A	OF3.5A	KD2.2m	KD2.2h	MS2.1A
Elphidium.crispum.crispum	0	17.6	19.8	5.9	0	0	0	11.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Elphidium.sp.	0	6	17.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cibicides.thiaracuta	0	0	11.6	14.7	9.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cibicides.sp.	0	6.8	0	5.1	0	14.7	16	0	0	0	0	0	0	0	0	0	0	9.8	0	0	0	0	0	0
Cibicides.molestus	0	0	0	0	0	0	7	0	0	0	0	0	0	0	6.5	0	0	10.5	0	0	0	0	0	0
Globocassidulina.sp	8	0	6	0	0	5.4	0	0	9.8	10.1	8.6	6.4	10.2	8.4	0	0	6.7	5.6	6.8	9.5	0	0	14.2	19.2
Cibicides.novozelandicus	0	0	0	6.6	0	0	0	6.1	11.2	8.6	16.6	6.1	0	6.3	0	0	0	7	0	0	0	0	0	0
Cibicides.perforatus	12.4	8	6.5	6.6	22.8	20.1	15.7	13.2	11.9	14.7	19.7	30.4	5.8	6.6	26.4	21.4	14.9	5.6	0	0	0	0	0	0
Cibicides.temperata	0	10.8	13.8	34.1	31.7	36.9	26.1	18.9	25.9	27.3	25.2	26.4	20.7	25.2	19.9	8.2	7.4	12.2	8.2	10.8	0	0	0	5.2
Astrononion.parki	0	0	0	0	5.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7.1	0	0	0	0
Elphidium.advenum.maorium	0	18.8	5.2	0	0	0	0	0	0	0	0	5.4	0	0	0	9.6	0	0	0	6.1	0	14.5	10.3	10.8
Anomalinoides.parvumbilia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	5.6	6.1	11.8	0	14.2	0	0
Bolivina.finlayi	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7.1	7.7	9.3	0	28.7	20.8	14.2	11.2
Bolivina.sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.9	0	0	0
Anomalinoides.awamoana	6.4	0	0	0	0	0	0	0	0	0	0	0	0	0	6.2	0	0	0	0	0	11.1	0	5.7	6.6
Buccella.lotella	0	0	0	0	0	0	0	5.4	0	0	0	0	0	0	13	0	0	0	0	7.4	11.4	8.3	0	5.2
Bolivina.pukeuriensis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8.7	6.2	8.2	0
Cassidulina.cuneata	0	0	0	0	0	0	7.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7.6	0	0
Bolivina.mahoenuica	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7.3	0	0
Elphidium.carteri	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.1	0	0	0	0	0
Bolivina.zedirecta	9.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bolivina.reticulata	8.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Trifarina.parva	8.8	0	0	0	0	0	0	0	0	0	0	0	7.5	6.6	0	0	0	0	8.6	0	0	0	0	6.6
Zeaflorilus.stachei	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.4	6.7	0	0	0	0	0	0	0
Virgulopsis.costata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10.6	0	0	0	0	0	0	0
Bolivina.subcompacta	0	0	0	0	0	0	0	0	5.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0



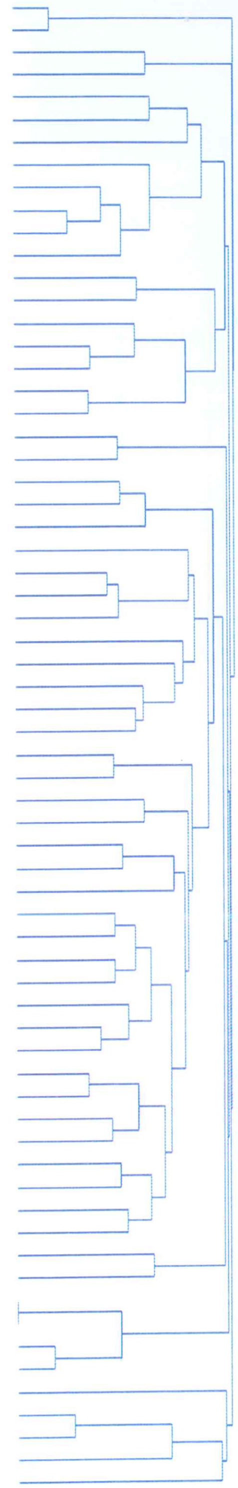


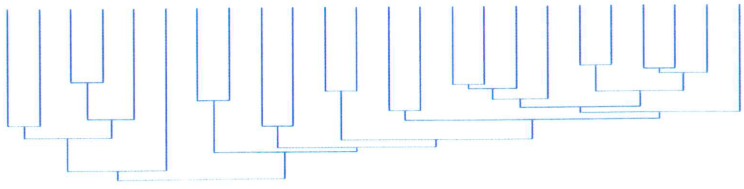
Appendix 3:
Detrended Correspondence Analysis: Species of foraminifera >5%



Appendix 3:
Bray Curtis Two-way Cluster Analysis: Rare Species and Planktics Removed

OF3.5A	KD2.2m	KD2.2h	MS2.1A	MS2.1E	KD2.2A	MB3.1H	KD2.2O	MB3.1A	DP10.4	DP15.1A	DP15.1e	DP14.2e	MS3.1E	DP3.5A	MB3.1R	MB3.1M	MB3.1P	MB3.1F	MS2.1M	OF3.4A	KD2.2f	OF3.4D	DP17.1A	Species
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.3	0	0	0	0	0	Polymorphina.sp.
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.8	0	0	0	0	0	Bulimina.sp.
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.2	0	0	0	0	0	0	Nonionella.sp.
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3.5	0	1.2	0	0	0	0	0	0	Trifarina.bradyi
0	0	0	0	0	0	0	2.5	0	0	0	0	0	0	2.9	0	0	0	0	0	0	0	0	0	Guttulina.yabei
0	0	0	0	0	0	0	1.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Elphidium.advenum.limbatum
2.3	0	0	0	0	0	0	1.7	1.2	0	0	0	0	0	0	0	0	0	0	0	1.9	0	2.3	1.1	Anomalinoides.pinguiglabra
2.7	0	0	0	0	0	0	0	0	0	0	0	0	0	1.1	0	0	0	0	0	0	0	0	0	Spiroloculina.disparilis
0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.1	0	0	0	0	0	0	0	1.1	0	Guttulina.sp.
0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.8	0	0	0	0	0	0	0	0	0	Planorbulinella.zelandica
0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.1	0	0	0	0	0	0	0	0	0	Melonis.simplex
0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.1	0	0	0	0	0	0	0	0	1.5	Nonionella.zelandica
0	0	0	0	0	0	0	0	0	0	0	0	1.1	0	0	0	3	0	0	0	0	1.1	0	0	Cribrotalia.dorreeni
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.5	0	0	0	0	0	0	0	Anomalinoides.macraglabra
0	0	0	0	0	0	0	0	0	0	0	1.5	3.8	2.6	0	0	0	0	0	0	0	0	1.1	0	Discorotalia.aranea
0	0	0	0	0	0	0	0	0	0	0	0	3.4	0	0	0	0	0	0	0	0	0	0	0	Discorotalia.tenuissima
0	0	0	0	0	0	0	1.3	0	0	0	0	2.3	0	0	0	0	0	0	0	0	0	0	0	Anomalinoides.subnonionoides
0	0	0	0	0	0	0	0	0	0	0	0	1.1	0	0	0	0	0	0	0	0	0	1.1	0	Notorotalia.spinosa
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.1	0	Lenticulina.loculosa
0	0	0	0	0	0	2.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.5	0	0	Textularia.sp.
0	0	0	0	0	0	1.8	0	0	0	0	1.1	0	0	0	0	0	0	0	0	0	0	0	0	Amphistegina.sp.
0	0	0	0	0	0	20.9	18.3	0	0	1.6	0	12.2	0	4.7	0	0	6.3	0	0	0	3.7	0	0	Elphidium.crispum.crispum
0	0	0	0	0	0	18.6	6.3	0	0	1.9	1.5	0	2.6	0	2	3.8	0	0	0	0	1.9	1.5	0	Elphidium.sp.
0	0	0	0	0	0	12.3	0	0	0	0	0	0	1.5	10.1	1.6	1.1	15.7	0	0	0	0	0	0	Cibicides.thiaracuta
0	0	0	0	0	0	0	0	0	0	0	2.3	0	0	0	0	0	0	0	0	0	0	0	0	Cribrotalia.ornatissima
0	0	0	0	0	0	0	0	0	0	7.4	6.8	3.4	2.6	0	0	0	0	0	0	0	3	0	0	Zeaflorilus.stachei
0	0	0	0	3.7	0	0	0	0	0	4.7	4.1	0	0	0	0	0	0	0	0	1.2	3.3	0	0	Nonionella.novozelandica
0	0	0	0	0	0	0	0	0	0	11.7	3.8	0	0	0	0	0	0	0	0	0	0	0	1.1	Virgulopsis.costata
1.2	0	0	1.1	1.2	0	0	0	0	0	0	0	0	1.5	0	0	0	0	0	0	0	1.5	0	0	Uvigerina.sp.
0	0	0	0	2.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Astrononion.pusillum
0	0	0	0	7.1	0	0	0	0	0	0	1.9	0	1.1	0	0	0	0	0	1.2	0	0	0	0	Elphidium.carteri
1.2	0	0	1.8	4.6	0	0	0	0	0	0	4.5	0	0	0	0	0	0	1.3	3.7	6.2	0	0	0	Bolivina.subcompacta
0	0	2.1	1.5	1.7	2	0	0	0	0	0	3.8	0	0	0	0	0	0	0	1.2	0	0	0	0	Bolivina.lapsus
0	8.4	3	0	0	0	0	0	1.2	0	0	0	0	0	0	0	0	0	0	2.5	0	0	0	8.3	Cassidulina.cuneata
0	8	2.6	0	3.3	0	0	0	2.4	2.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Bolivina.mahoenuica
1.2	1.5	1.7	4.4	0	0	0	0	0	1.6	0	0	0	0	1.4	0	0	1.2	2.2	1.6	0	0	1.1	1.9	Anomalinoides.sp.
6.5	1.1	0	1.8	0	0	0	0	0	4.4	2.3	0	1.1	0	1.1	0	0	0	0	1.6	0	0	0	0	Bolivina.sp.
0	0	3	1.8	2.9	1.5	0	0	4.3	0	1.2	0	0	0	0	0	2.3	2	0	1.2	0	0	1.5	0	Discopulvinella.bertheloti
0	0	3.4	0	0	4.5	0	0	5.5	2	2	1.9	1.1	0	0	1.6	0	2.4	0	0	0	0	0	0	Gyroidinoides.zelandicus
0	0	1.3	0	0	3.5	0	5	0	0	0	2.3	1.9	3.3	0	0	0	3.5	0	0	4.3	1.5	0	1.5	Sphaeroidina.bulloides
2.3	2.3	4.9	2.6	3.7	0	0	0	8.2	0	3.9	3.4	2.3	2.6	5.8	2.7	3.4	0	4.4	4.1	0	2.6	3.1	0	Astrononion.parki
1.5	15.6	1.3	1.5	7.1	0	0	0	13.7	6.4	4.7	5.3	3.1	0	0	1.2	0	2	4.4	1.2	0	3.3	0	0	Anomalinoides.parvumbilia
1.5	16	12.3	11.3	0	0	5.5	19.6	7.1	0	5.1	10.1	4.2	1.9	0	5.9	0	3.5	4.8	4.1	0	2.2	0	1.5	Elphidium.advenum.maorium
31.9	22.9	17	11.7	10.8	2.5	1.8	4.6	4.7	8.8	7.8	1.9	3.4	1.5	0	2	0	0	0	4.5	0	0	1.1	1.9	Bolivina.finlayi
12.7	9.2	2.1	5.5	2.1	0	2.3	1.7	8.6	0	0	3.8	5.7	13.3	0	0	0	0	3.1	4.1	1.6	0	0	1.1	Buccella.lotella
12.3	3.4	6.8	6.9	5.4	8	0	0	0	0	0	0	0	6.3	0	0	0	0	0	1.2	3.1	3.3	0	0	Anomalinoides.awamoana
9.6	6.9	9.8	1.8	3.3	4.5	0	0	2	0	0	0	0	0	0	0	0	0	0	3.7	0	0	0	0	Bolivina.pukeuriensis
0	0	0	3.6	5.4	15.4	6.8	8.3	1.2	6.4	16.4	22.6	14.1	27	23.8	33.3	21.1	7.1	8.4	7	13.2	15.2	21.8	17	Cibicides.perforatus
1.5	4.6	4.7	5.5	9.5	4.5	14.5	11.3	12.5	13.9	8.2	8.6	20.2	20.4	33.2	29	38.9	36.5	31.7	25	28.7	28.3	28	28.4	Cibicides.temperata
5	0	17	20.1	7.9	10	6.4	3.8	11	6.4	7.4	4.5	3.8	1.5	4.3	7.1	5.7	5.1	10.6	12.3	10.9	10.4	9.6	0	Globocassidulina.sp
0	0	0	1.1	0	0	2.3	3.3	5.1	8	0	1.5	6.5	0	2.9	6.7	0	7.1	7.9	4.5	12.4	8.9	18.4	2.3	Cibicides.novozelandicus
0	0	1.3	4	5.8	0	0	2.1	0	3.2	1.6	0	1.5	0	0	0	0	0	1.8	2.9	3.9	1.5	1.9	2.3	Bolivinella.bensoni
5.4	0	1.3	6.9	10	10.9	2.7	2.1	3.5	5.6	1.2	0	0	1.1	0	0	0	0	8.4	9	1.6	2.6	2.3	2.7	Trifarina.parva
0	0	2.6	2.6	0	2	0	0	2.7	11.9	3.5	0	0	6.7	0	0	2.6	0	5.3	0	4.3	1.5	0	7.6	Cibicides.molestus
1.2	0	1.3	0	1.7	0	1.8	7.1	1.2	11.2	4.3	3	3.4	2.6	3.6	3.5	15.5	5.5	2.6	3.3	4.3	2.6	2.7	17.4	Cibicides.sp.
0	0	0	1.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Epistominella.cassidulinoides
0	0	0	1.5	0	0	0	0	0	0	3.1	0	0	0	0	0	0	0	0	0	0	0	0	0	Mississipina.concentrica
0	0	0	0	0	4.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Anomalinoides.fasciatus
0	0	0	0	0	4.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Lagena.solena
0	0	0	0	0	11.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Bolivina.zedirecta
0	0	0	0	0	10.4	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	1.1	Bolivina.reticulata
0	0	0	0	0	0	0	0	1.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Textularia.miozea
0	0	0	0	0	0	0	0	0	1.6	0	0	0	0	0	0	0	0	0	0	0	0	0	1.1	Cibicides.vortex
0	0	0	0	0	0	0	0	0	1.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Arenodosaria.antipoda
0	0	0	0	0	0	0	0	2.7	2.8	0	0	0	0	0	0	1.1	0	0	0	1.6	0	0	0	Lagena.sp.
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.2	0	0	0	Bulimina.n.sp.cf.aculeata





Appendix 3:
Detrended Correspondence Analysis: Species of foraminifera >5%